HAZARDOUS CONTAMINANTS PROGRAMME

THE ENVIRONMENTAL ASPECTS OF RADIOACTIVE SUBSTANCES IN ONTARIO

A BACKGROUND REPORT

REPORT NO. ARB-TDA-61-79

JULY 1979

Ontario
Ministry of the Environment

The Honourable
Harry C. Parrott, D.D.S.,
Minister

Graham W. S. Scott, Q.C.,
Deputy Minister

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Prepared For:

Air Resources Branch

Ontario Ministry of the Environment

By:

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Willowdale, Ontario

May, 1978

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Dear Dr. Gewurtz:

Re: Hazardous Substances Program: the Environmental Aspects of Radioactive Substances in Ontario - A Background Report

We are pleased to present our final report on the Environmental Aspects of Radioactive Substances in Ontario.

The information contained in this overview report was compiled from previous studies, literature reviews and interviews with knowledgeable individuals. The principal study effort was directed towards identifying potentially significant sources of radioactive emissions to the environment. No potentially significant uncontrolled sources of radioactivity to the environment were identified during the course of this study. In addition to source identification the potential health effects associated with exposure to radiation are also reviewed in considerable detail. The other aspects of environmental radioactivity discussed in this report have not been as extensively reviewed because of constraints on time and funds. However, considerable effort was directed towards compiling a bibliography of material related to environmental radioactivity. It is hoped that this bibliography will guide those interested in pursuing the various aspects of this subject.

We appreciate the opportunity of working on this interesting project and would like to thank you for your assistance in reviewing draft sections of the report.

Yours very truly,

E. Koczkur
Project Director

D.B. Chambers
Project Manager

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James F. MacLaren Limited would like to thank Dr. R.B. Sutherland for the time, effort and care he put into the health effects section of this report.

We would also like to thank Dr. S. Gewurtz for his careful review of all sections of the report.

This report, with the exception of Chapter 5, was prepared by Dr. D.B. Chambers (physicist), John Jarrell (chemical engineer), Pat Mellor (chemical engineer), Dr. Leo Lowe (physicist), Dr. Tom Watson (Biologist) and the project engineer, Valerie Cassaday (physicist), all members of the staff of James F. MacLaren Limited. Any errors in this document are solely the responsibility of James F. MacLaren Limited.

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Introduction 1

1.1 Introduction to the Report

Since 1974, the Ministry of the Environment (MOE) has been working to systematically identify and assess hazardous situations created by industrial discharges and emissions of toxic substances. Under the Ministry's Hazardous Substances Programme (HASP), comprehensive investigations are conducted on specific high risk pollutants, and subsequent control/ abatement programmes may be recommended. The overall objective is to anticipate environmental problem areas which may be encountered in Ontario at some future date, and to recommend preventative or remedial action before a serious threat is posed to the community.

This report presents the results of an overview survey of the various aspects of radioactive substances which are relevant to the role of these substances as environmental pollutants in Ontario, and as such represents a segment of the Hazardous Substances Programme.

In view of the existing and probable future status of the nuclear industry in this province, radioactive substances were identified by the MOE as high priority for environmental evaluation on the basis of the following criteria:

(i) potential human health effects;

(ii) significant industrial usage and production in Ontario;

(iii) potential for entering the environment in significant amounts; and

(iv) persistence in the environment.

It is hoped that this overview report will provide a suitable basis for MOE strategy determination in the area of radioactive substances.

The detailed terms of reference for this contract can be found in Appendix IV, located at the end of this report.

This study, conducted over a three month period, includes the findings of literature searches and interviews with selected groups. Because of budgetary and schedule constraints, it is possible that certain additional sources of environmental radioactivity could be identified through a more exhaustive study programme.

Every attempt has been made in this report to present the data in as 'non-technical' a fashion as possible in order to assist the non-specialist reader. References are included after each chapter to indicate the basic material which was used as a resource for that section. An overall bibliography has also been included at the back of this report to provide the interested reader easy access to a wide variety of related literature.

This report discusses the information reviewed during the study under the following headings:

Chapter 1, Introduction, contains a brief introduction to radioactivity, identifies those radionuclides of most interest and introduces the concept of environmental pathways.

Chapter 2, Sources, details the possible ways that radionuclides (natural or artificial) may enter the environment. Model facilities are described when applicable.

Chapter 3, Pollution Control, briefly describes methods of reducing or eliminating releases of radioactivity into the environment.

Chapter 4, Environment, describes some of the important pathways of radionuclides in the environment.

Chapter 5, Health Effects, discusses how ionizing radiation may affect humans, including documented exposures and theoretical assumptions.

Chapter 6, Radiation Protection Criteria, outlines the development of regulations to protect humans, with a discussion on the philosophy behind these regulations.

Chapter 7, Monitoring, discusses the objectives of radiological monitoring programs.

Appendix 1	contains a glossary of terms commonly used in reference to radioactivity.
Appendix 11	contains a summary of radiological monitoring presently being conducted in Ontario.
Appendix 111	contains a bibliography of related texts and articles, to serve as a guide for further reading on the topics discussed in the report.
Appenxix IV	contains the terms of reference of this report.

1.2 Introduction to Radioactivity

All materials in this world are mixtures or chemical combinations of elements. The smallest unit of an element is the atom which is the smallest portion of the element that can exist and still keep the identity of that element. The atom is often referred to as the building block of all matter.

All atoms are composed of three basic atomic particles: electrons, protons and neutrons. The atom has a densely packed center called the nucleus, which contains protons and neutrons. Electrons orbit around this nucleus.

Protons and neutrons are approximately equivalent in mass and constitute most of the atom's weight. A proton has a unit positive charge, an electron has a unit negative charge, and a neutron is electrically neutral. The atom is also electrically neutral, because it contains the same number of protons and electrons.

The chemical properties of an atom are determined by its number of charged particles. Because neutrons have no charge, they do not affect the chemical properties of the atom. Atoms with identical numbers of protons (and electrons) but different numbers of neutrons are chemically similar and called isotopes (i.e. variations) of an element.

Atomic nuclei "stay together" because they are energetically stable. If nucleus is not stable, it changes to a stable state by emitting energy in the form of electromagnetic waves and/or in the form of kinetic energy associated with the emission of particles travelling at high velocity. The emitted particles and/or released energy are both called "radiation". The process of emitting radiation is called decay or disintegration.

Electromagnetic waves exhibit wave-like properties such as reflection, refraction, dispersion, interference and diffraction. The most important electromagnetic radiations are gamma rays, x-rays, ultraviolet, visible light, infrared or heat rays, and radio waves of various lengths. These radiations differ primarily in their wavelengths. Gamma rays are the shortest electromagnetic radiations, having wave-lengths ranging from 0.001 to 1 Angstrom in length (10^{-13} to 10^{-10} metres). The other electromagnetic radiations listed above are in order of increasing wave-length. Of the various electromagnetic radiations, only gamma rays and x-rays are of interest in this report, since they both constitute one form of ionizing radiation. Gamma rays are produced by the natural or artificial disintegration or decay of atomic nuclei. Most exposure to x-rays results from their artificial production by x-ray machines, television sets or certain scientific or industrial equipment.

Particulate or corpuscular radiations are also produced by atomic disintegration. The most important categories of particulate radia-

tion comprise alpha particles, beta particles, neutrons and protons. All are characterized by having mass, and with the exception of the neutron, all possess electrical charge. The alpha and beta particles are of main concern in this discussion since they are the predominant types of particulate radiation.

An alpha particle is made up of 2 protons and 2 neutrons. It thus has a positive electrical charge of two units.

A beta particle is an electron released from the nucleus. This electron is produced when a neutron converts to an electron and a proton. The proton stays in the nucleus and the electron is ejected from the atom. The beta particle has a negative electrical charge of one unit. (Positrons or positive beta particles exist but are less common).

Gamma rays, x-rays and the various particulate radiations are called ionizing radiations because in depositing energy in the materials through which they pass, they cause ionization, i.e. they dislodge electrons from atoms and thereby create electrical imbalances great enough to break up one or more of the chemical bonds which link atoms into molecules. This alteration is expressed initially in living tissues as an intracellular change, the consequences of which may not become manifest until later in the form of cell death or a delayed injury of some kind.

The distance travelled by the ionizing radiation will depend on its energy when it is emitted and on how it interacts with the atoms along its path. In general, the larger the particle, the more frequent are its interactions. Thus an alpha particle has very little penetrating power; it will interact with many atoms in its path and lose its energy very quickly. For example, an alpha particle will usually not penetrate a sheet of paper. A beta particle is much lighter, and will not interact with as many atoms per unit length as does the alpha particle. A sheet of aluminum will stop a beta particle.

Neutrons possess greater penetrating power. Since they carry no electrical charge, their interaction with matter is entirely dependent upon a direct collision between a neutron and the nucleus of an atom. Such collisions can then result in the production of ions in the tissues through which the neutrons pass.

Gamma and x-radiation, having no mass, can only be stopped by thick sheets of lead or concrete.

Human exposure to radiation can be characterized as external or internal.

External exposure refers to radiation received from outside the body. External alpha radiation presents little hazard, because alpha particles usually cannot penetrate clothing and/or the outer layer of skin

which is composed of dead cells. Radiation can do no harm to these dead cells. On the other hand, beta radiation can penetrate a few millimetres of living tissue, potentially far enough to produce injury. The more penetrating gamma radiation will reach such important organs as the blood-cell-producing bone marrow.

Internal exposure refers to radiation received from within the body. Radioactive and non-radioactive isotopes of the same element cannot be distinguished chemically. Thus radioactive isotopes can be chemically incorporated into the body if they are swallowed or inhaled. There they disintegrate, releasing radiation internally. In this case, alpha radiations become very important because they release all of their energy in a short path length, thus having a greater effect on the cells with which they interact. Exposure to beta radiation is also a more severe problem when deposited internally, rather than from external sources.

Laws of Radioactive Decay

Isotopes of elements that are radioactive are called radionuclides or radioisotopes. The rate at which these radionuclides decay varies a great deal from one isotope to another. Each isotope has a characteristic radioactive decay constant (λ). The time scale for decay can range from fractions of a second to billions of years. The rate of decay is always the same for a particular radioactive isotope: it makes no difference whether the isotope is in a solid, liquid or gaseous state; temperature or pressure will not affect it; it remains essentially unchanged when the isotope is combined chemically.

The decay constant usually denoted (λ) gives the probability per unit time that an atom in a sample will decay. The actual number of atoms decaying per unit time is known as the activity of a sample. The activity can be obtained by multiplying the probability of decay per unit time by the number of atoms in the sample at any one time.

The term "half-life" (or better "physical" half-life, denoted by $T_{1/2}$) is very often quoted to indicate the longevity of a radionuclide. This is simply the amount of time it takes for one-half of the atoms in a given amount of nuclide to decay or disintegrate. The half-life varies inversely with λ, since the faster the decay rate, the less time it should take the sample to decay (and vice versa).

Thus, in assessing the potential effects of radioactivity, one must consider the type of radiation that radionuclides will emit, as well as the potential of the radionuclides for damage, how they may combine chemically, how they may reach humans, whether they are likely to cause internal or external exposure and how long and where they will persist in our environment.

(The glossary at the end of this report provides the reader with definitions of some of the more common terms used in discussing radioactivity and radioactive substances.)

Units

It is useful to have an understanding of the units used to describe radioactivity. The roentgen, rem, rad and curie are of particular interest. The roentgen (R) is the quantity of X- or gamma radiation which produces one unit of electrostatic charge in 0.001293 grams of air (1 cc of air at STP). This is a rather outdated unit and not particularly useful, since it does not apply to all types of radiation. The rad and the rem are more useful terms for our purposes since they may be used to measure any type of ionizing radiation. The rad is a unit which defines the energy potential of the radiation: one rad is the quantity of radiation which imparts 100 ergs of energy to one gram of irradiated matter. The rem is a special unit, often used in reference to living tissues, which takes into account the differing biological effects of various radiations, as discussed below.

As pointed out by Dudley (1), the concept of radiation dose is analagous to that of temperature rather than to that of heat. It denotes the concentration of energy deposited in matter, rather than the amount. Just as raising the temperature of a finger by ten degrees would cause little more than discomfort whereas raising the temperature of the body by ten degrees would be fatal, in a similar fashion a dose of 500 rads to a finger would be almost inconsequential, whereas a dose of 500 rads to the whole body would probably be lethal. Thus, the biological effect of a given quantity of radiation depends not only on the magnitude of the dose but on the organ or tissue region and mass receiving it.

It has been found that equal absorbed doses (measured in rads) from different kinds of radiation may not produce the same biological effects. To correct for these differences, the relative biological effectiveness (RBE) of various types and energies of radiation were determined experimentally, using a variety of biological end-points such as death of the animal, cataract formation and spleen-thymus weight loss. Multiplying the absorbed dose (in rads) by the RBE for the particular radiation involved gave the "dose equivalent" the unit for which is the rem (roentgen equivalent man). The rem is intended to express the dose delivered to man by any ionizing radiation which is biologically equivalent to 1 roentgen of x-ray or gamma radiation. Unfortunately, however, the RBE varies not only with the type and energy of the radiation but also with the particular biological end-point, dose rate, accumulated dose, dose distribution, body organ under study, etc. Thus in calculating the skeletal burden of strontium-89 and 90 and of plutonium-239 that would result in the same damage as is produced by radium-226 it was found that it requires only one fifth as much RBE dose from these radionuclides as from radium-226 to produce the same bone damage - measured primarily in terms of bone tumour production. To compensate, a relative damage factor, n, was introduced for application when bone is the critical organ. Because the RBE dose does not include the relative damage factor, the International Commission on Radiological Protection

(ICRP) subsequently recommended that the term RBE be used in radiobiology only, and that for radiation protection the name "quality factor" (QF) be substituted for RBE. The ICRP also recommended that the term RBE dose be discontinued and that it be replaced by "dose equivalent" (DE) which is defined as

DE (in rems) = adsorbed dose (in rads) X QF_1 X QF_2 X QF_3 X ... in which QF_1 = RBE, QF_2 = n (relative damage factor), and QF_3 = other factors as needed (1).

For beta and positron particles and for x-ray and gamma radiation, the value used for the RBE or QF_1 is 1. For neutrons the most recent value for QF_1 is given as 10, and for alpha particles the most recent value is 20 (2).

It should be emphasized that there is not complete agreement among scientists upon these latest values. Until recently, it was more customary to assign RBE values of 5 for neutrons and 10 for alpha radiation in calculating the dose equivalent received by particular organs. Using these RBE or QF_1 values, an adsorbed dose of 1 rad of neutrons would result in a dose equivalent of 5 rems, and an adsorbed dose of 1 rad of alpha radiation would deliver 10 rems. To state the converse, an allowable dose of 5 rems (strictly, the allowable dose equivalent) for a given organ could be made up of 5 rads of x-ray or gamma radiation, or 1 rad of neutrons, or 0.5 rads of alpha particles. The dose equivalent approach enables exposures of different kinds of radiation to be summed, at least roughly, in terms of their biological effects and compared with recommended dose limits. However, it should be remembered that the choice of different RBE or QF_1 values used by different scientists in assessing dose response relationships thus introduces a variable which may result in different estimates of the biological risk associated with exposure to past radiation in the same human or animal population (1).

The curie (ci) is a unit which is used to measure the amount of radionuclide present, rather than the energy of any radiation that it may give off. It is a quantity of radioactive material in which 3.7×10^{10} atoms disintegrate every second. This is a large unit and therefore the picocurie (pCi)(0.037 disintegrations per sec or 2.22 disintegrations per minute) is more commonly used.

A pCi, which strictly denotes the number of disintegrations with time, cannot be converted to an energy unit (i.e. rem, rad or roentgen) unless the specific radionuclide being discussed is known. There is thus no simple conversion factor from pCi to rads or rems.

The difference between radiation-dose and radiation-exposure should be emphasized here. Dose refers to the amount of energy absorbed by the material. Exposure is a measure of the ionization produced in the air. Thus, the roentgen is the unit of exposure and the rad and the rem are the units of dose.

New units are now being used to replace rems, rads and curies; they are:

1 Seivert (Sv)	=	100 rem
1 Gray (Gy)	=	100 rad
1 Becquerel	=	1 disintegration/sec (replaces Curie) (1 pCi = 2.22 disintegrations/min)

These are international (SI) units.

Note — When an element is written in this report, i.e. radium, it will usually be followed by its mass number(A) which identifies which isotope it is, i.e. radium-226.

The mass number is equal to the sum of the number of protons and neutrons.

1.3 Radionuclides of Interest

Both naturally occurring radionuclides and those radionuclides that result from fission or activation are of interest to this report.

Natural Radionuclides

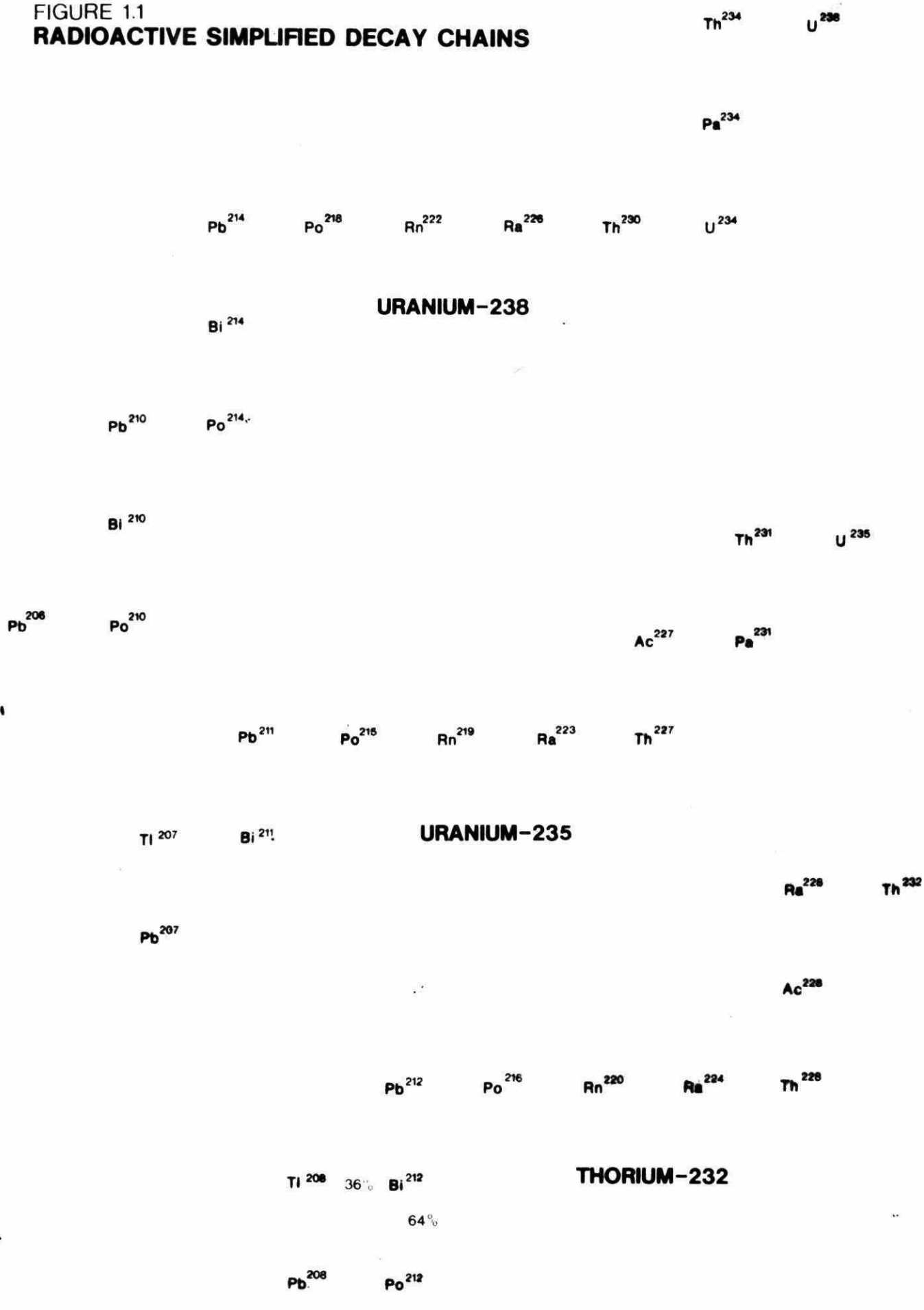
(i) Primordial Radionuclides

The majority of these are isotopes of the heavy elements and belong to the Uranium-238, Uranium-235 and Thorium-232 decay chains (see Fig. 1.1). (When a radioactive isotope decays it changes into an isotope of another element. This new atom may be stable, but in many cases it is not. If this new atom is not stable it will also decay, changing into yet another new kind of atom. This process continues through a chain of isotopes, until a stable form is reached. In this series, the isotope in its original form is usually called a parent, and in its subsequent forms it is referred to as a daughter).

In the uranium-238 decay chain, the radon daughter products, listed below, have other, commonly used names:

Historical Name	Current Name
Radon (Rn)	Radon-222
Radium A (RaA)	Polonium-218
Radium B (RaB)	Lead-214
Radium C (RaC)	Bismuth-214
Radium C' (RaC')	Polonium-214
Radium D (RaD)	Lead-210
Radium E (RaE)	Bismuth-210
Radium F (RaF)	Polonium-210
Radium G	Lead-206

FIGURE 1.1
RADIOACTIVE SIMPLIFIED DECAY CHAINS



Due to increased interest in radon and radon daughters in recent years, a special unit of concentration, the working level (WL), has been devised to give a measure of the total radiation energy and hence the potential hazard associated with the short-lived radon daughter products in a given quantity of air. The working level is defined as "any combination of the short-lived decay products of radon (RaA, RaB, RaC and RaC') in 1 litre of air which will result in the ultimate emission by them of 1.3×10^5 MeV of α particle energy"(5).

If radon and its short-lived daughters are in equilibrium, then 1 WL is equivalent to 100 pCi/l of radon (and, since equilibrium exists, 100 pCi/l of each of the short-lived daughters). However, such an equilibrium state seldom occurs, in which case it is necessary to know the state of disequilibrium in order to convert the radon level to working levels. The disequilibrium factor (F) is the multiplier used in this conversion.

F is variable in practice and rarely has a value of one. Any process which removes the daughter products, particularly movement and dilution of the air, will ensure that F remains less than one (4).

The major primordal radionuclides which decay directly to stable atoms (i.e. they do not decay in a series of steps) are potassium-40 and rubidium-87. Potassium-40 makes up only 0.0118% of all of the isotopes of potassium, but potassium is so widespread that potassium-40 contributes about one-third of the dose to man from natural background radiation. Rubidium-87 makes up a larger percent of all rubidium isotopes, but rubidium abundance in the earth's crust is two orders of magnitude less than potassium (6).

(ii) Cosmogenic Radionuclides

Cosmogenic radionuclides have been found in man, in the sea, in the sediments, on the ocean floor, in the biosphere, topsoil, polar ice, surface rock and atmosphere.

They occur mainly in the middle or lower regions of atomic numbers. They are produced by the interaction of cosmic rays (primarily protons) with target atoms in the atmosphere or in the earth.

These radionuclides are beta and gamma-ray or x-ray emitters, and range in half-life from millions of years down to a fraction of a second (6).

In considering exposure to man, the four major contributors are carbon-14, tritium, beryllium-7 and sodium-22. All of these except beryllium-7 are isotopes of major elements in the body and have been found to contribute a measurable dose to man (6).

(iii) Cosmic Radiation

Cosmic radiation consists of charged particles, primarily protons, which enter the earth's atmosphere with energies high enough to generate

secondary particles that penetrate to ground level. These secondary particles are mostly high energy muons and electrons, and they produce ionization in ground-level air at a rate comparable to that from beta and gamma radiation generated by terrestrially-distributed radionuclides (6).

Fission and Activation Products

This category is composed of radionuclides created by man's activities. Fallout from atmospheric nuclear weapons testing and the nuclear fuel cycle are the two primary sources of fission and activation products. The main radionuclides from both sources are listed in Table 1.1.

(i) Nuclear Weapons Testing

The main radionuclides produced by nuclear weapons testing are cesium-137 and strontium-90. Both elements are rather widespread, since they are produced and dispersed in the atmosphere. This class of radioactivity has been well studied and monitored in some detail within the past few years. Chapter 2 provides further details.

(ii) Nuclear Fuel Cycle

Table 1.1 shows the main artificial radionuclides that are created in the nuclear fuel cycle. These would all result from a nuclear power station operation. When discussing the nuclear fuel cycle, the natural radionuclides released into the environment are usually considered in conjunction with these man-made fission and activation products. Fig. 1.2 shows a very general schematic of the Candu nuclear fuel cycle. It indicates the types of radionuclide emission from the major steps in this cycle.

There are three significant entry points:

(a) airborne releases through the stack,

(b) liquid effluents through the water cooling system and

(c) reject streams from the heavy water upgrading plant.

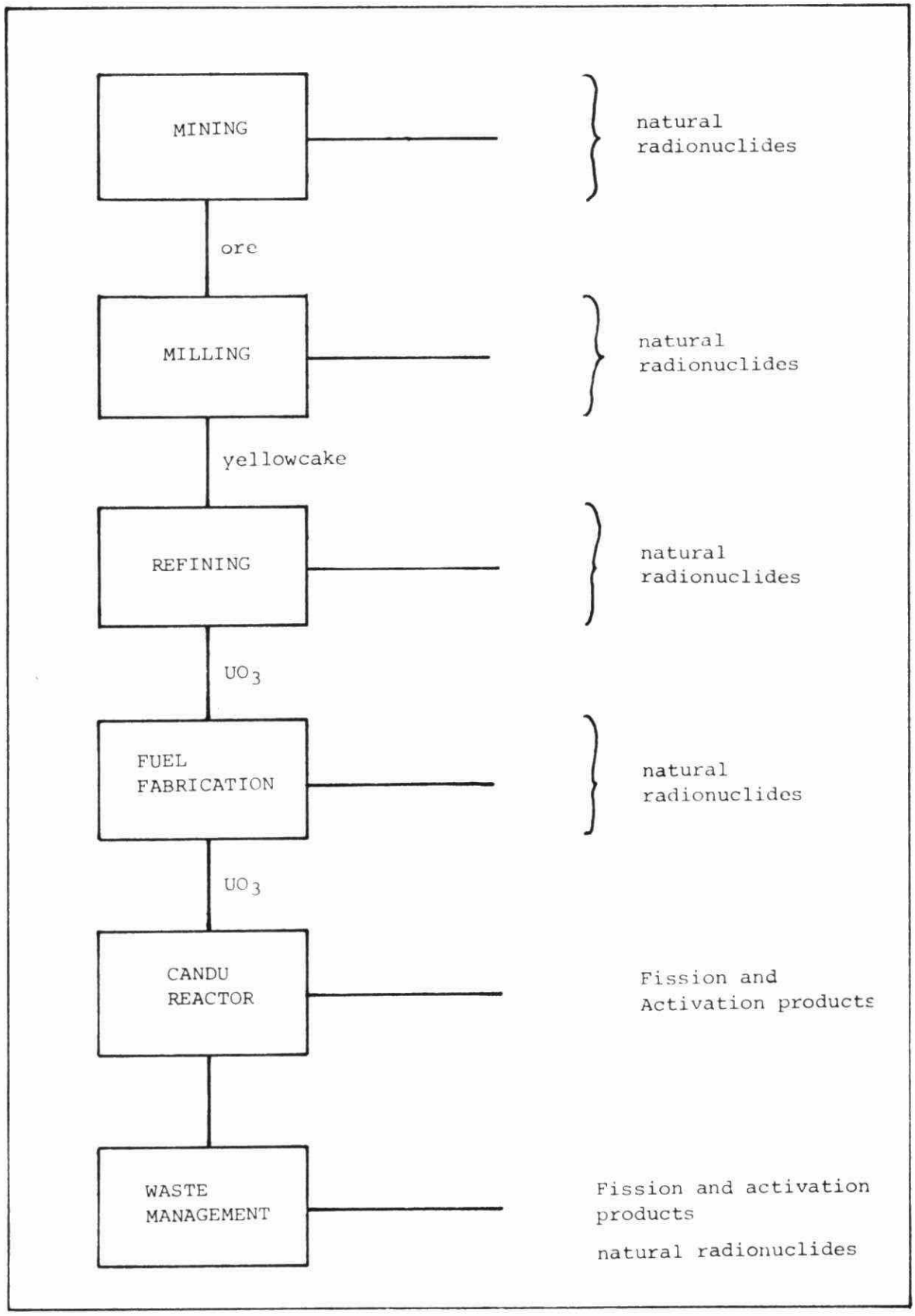
The released radioactive materials will affect the terrestrial biosphere, the aquatic environment, and man.

1.4 Environmental Pathways

The previous sections have outlined, in general, how radionuclides enter the environment. Once in the environment, radionuclides may enter a number of pathways. As dust or gases they may be transported to places distant from the source. They may enter the water system either directly, or indirectly as fallout. They may be deposited in the soil. The radionuclides enter into plant and animal pathways from these

NUCLEAR FUEL CYCLE: MAIN POTENTIAL RADIOACTIVITY RELEASE POINTS

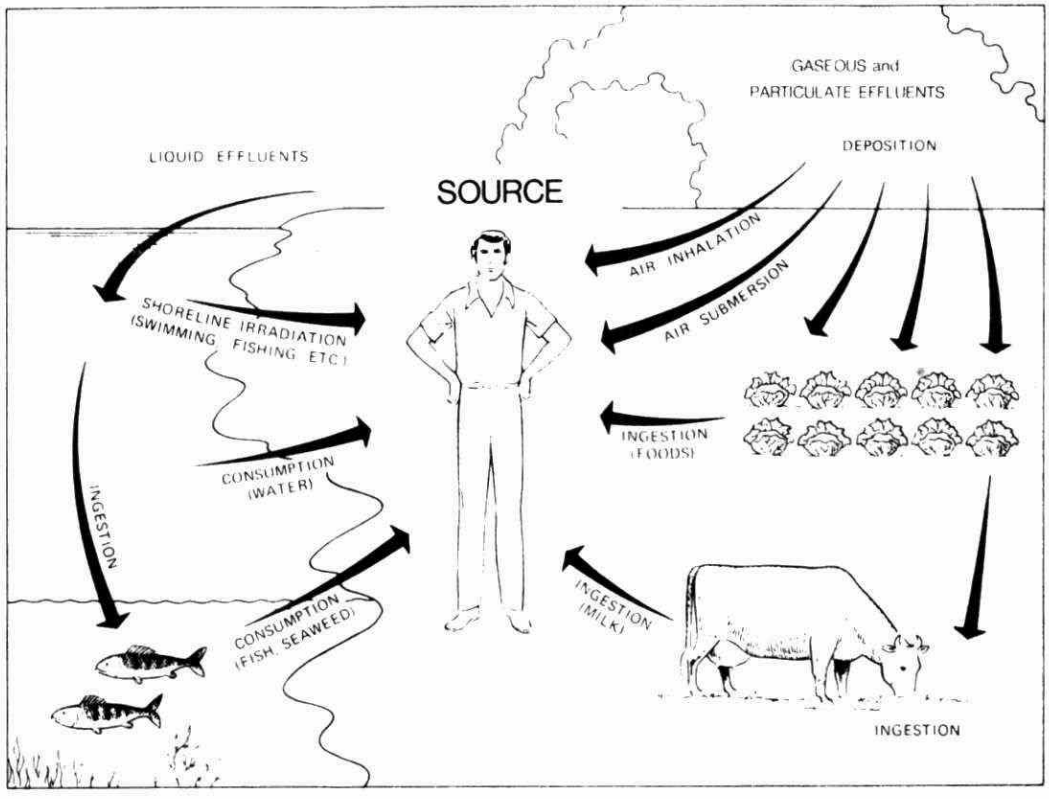
Figure 1.2



GENERALIZED EXPOSURE PATHWAYS

Figure 1.3

GENERALIZED EXPOSURE PATHWAYS FOR MAN



GENERALIZED EXPOSURE PATHWAYS
FOR ORGANISMS OTHER THAN MAN

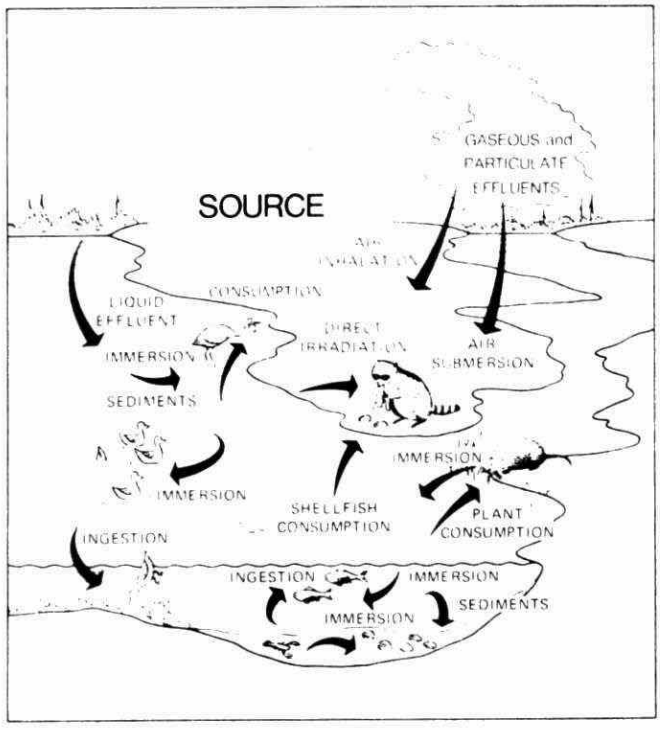


TABLE 1.1(7)

MAJOR RADIONUCLIDES RESULTING FROM FISSION AND ACTIVATION (MAN-MADE)

I Nuclear Weapons Test:

Cesium-137)
Strontium-90) relatively large amounts

Ruthenium-106
Cerium-141
Cerium-144
Europium-155
Hydrogen-3 (tritium)

II Nuclear Fuel Cycle:

H-3
Cr-51
Mn-54
Fe-55
Fe-59
Co-58
Co-60
Zn-65
Sr-89
Sr-90
Zr-Nb-95
Ru-103
Ru-106
Ag-110m
I-131
Cs-134
Cs-137
Ba-La-140
Ce-141
Ce-144
Noble gases: krypton
xenon
argon

(See Chapters 2 and 5 for further discussion)

points. Thus man is exposed to radionuclides by direct and indirect pathways. Fig. 1.3 shows generalized exposure pathways for man and organisms other than man. A more detailed description of environmental pathways can be found in Chapter 4.

References - Introduction

1. Dudley, Robert A. "Natural and artificial background of man", reprinted from, "Low Level Irradiation" Washington D.C.: American Association for the Advancement of Science, 1959.

2. International Commission on Radiological Protection. "Recommendations of the international commission on radiological protection". ICRP Publication 26. Oxford: Permagon Press, 1977.

3. U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The effects on populations of exposure to low levels of ionizing radiation". Washington, D.C.: National Academy of Sciences, 1972.

4. Basuk, Jack and Nichols, A. "An overview of the ionizing radiation hazard in Canada. "National Science Council of Canada, Policies and Poisons Committee, 1977.

5. Evans, Robert D. "Engineers guide to the elementary behaviour of radon daughters". Health Physics 17 (1969)" 229-252.

6. U.S. National Council on Radiation Protection and Measurements. "Natural background radiation in the United States". NCRP report No. 45. Washington, D.C.: NCRP., 1975.

7. MacLaren Atlantic Limited et al. "Preliminary Environmental Impact Statement - Lepreau Nuclear Generating Station" Moncton: n.p., 1974.

8. Canadian Nuclear Association, "Nuclear power in Canada, questions and answers". Toronto: Canadian Nuclear Assoc., 1975.

9. Soldat, J.K. "Aquatic Exposure Pathways - potential exposure to man from Environmental Transport of Waste Radionuclides. Richland, Washington: Batelle, Pacific Northwest Lab., 1976

10. Wade, James E. and Cunningham, G.E. "Radiation monitoring, a programmed instruction book". Oak Ridge, Tennessee: U.S. Atomic Energy Commission, Technical Information Centre, 1967.

11. Rothschild, H.C. "A criteria digest on radioactivity in the environment". National Research Council Canada no. 13566. Ottawa: National Research Council Canada, 1973.

12. Evans, Robley D. "The atomic nucleus" Toronto: McGraw-Hill, 1955.

13. Fry, R.M. "Radiation hazards in uranium mining and milling". Atomic Energy (October 1975): 12-31.

14. Beckmann, Petr. "The health hazards of not going nuclear. "Boulder, Colorado: The Golum Press, 1976.

Sources of Radioactivity 2

Introduction

The main types of radiation that may affect the environment in Ontario were briefly outlined in Chapter 1. These two main categories were natural radiation and radiation from fission and activation products.

Natural radiation may be further divided into radiation not affected by man's activities and a second category where the radionuclides, although naturally occurring, are definitely influenced by man's activities.

The fission and activation products are produced solely by man's activities. The most obvious source of these products is the nuclear reactor.

This chapter identifies the principal sources of radioactivity which affect the environment in Ontario, and where possible, provides an indication of the quantity of radioactivity released.

2.1 Natural Sources of Radiation Exposure

(i) Introduction

The largest source of ionizing radiation exposure to the world's population is the natural radiation environment. This exposure is highly variable and dependent upon a number of factors such as altitude, geological features and living habits. As noted by Oakley (1), this variation alone often exceeds exposures from man-made sources which receive considerably more attention, and are discussed in other sections of this report. In order to better assess the significance of the effects of manmade sources of exposure to the population, it is necessary to determine the larger and more pervasive component due to natural radiation.

The following sections discuss the sources of natural radiation exposure. Most of the data discussed are from non-Canadian publications (1, 2, 3, 4). However, the data are thought to be generally representative of the radiological quality of the Ontario environment.

(ii) Sources of Natural Radiation

Natural radiation exposure can be generally divided into two classes, terrestrial and extra-terrestrial. Both of these have an external component of radiation impinging on man from outside the body and an internal component where radioactive materials are taken into the body by ingestion or inhalation.

Extra-terrestrial sources are direct cosmic radiation and cosmogenic radionuclides (radionuclides produced by cosmic radiation). Terrestrial sources of external exposure are radioactive elements in the earth's crust and in building materials, and, to a lesser extent (<5% of total), the decay products radon (radon-222) and thoron (radon-220) in the atmosphere(1).

(iii) Cosmic Radiation Exposure

Cosmic radiation consists of charged particles (protons 87%, alpha particles 11%, heavy nuclei and electrons 2%) which are incident on the earth's atmosphere and have sufficient energy to generate secondary particles that penetrate to ground level. These secondary particles, primarily muons and electrons plus some neutrons, result in radiation at ground level comparable to the beta and gamma radiation generated by terrestrial radionuclides(4). The radiation dose from cosmic radiation is about 44 mrem/y in Canada.

The ultimate source of these particles is not well understood although the highest energy particles and a significant fraction of the total radiation may be extra-galactic. The relatively low energies of particulate radiation from our sun precludes its secondary radiation from reaching the earth's surface except during occasional solar flares.

Cosmic radiation varies with time. This variation is due to solar activity (which follows an 11-year cycle and reversals of the earth's magnetic field, (which occur about every 10^4 years). However, average cosmic ray levels have remained relatively constant for at least 10^8 years. Variations of latitude, although significant on a global scale (8 to 10%), seem to be negligible on a province-wide scale. Altitude variations are more significant and these cause most of the differences in individual external exposure. At sea level, the cosmic radiation dose equivalent is about 40 mrem/y while at 10,000 feet, it is about 160 mrem/y(1). It is interesting to note that the dose rate at jet cruising altitudes is approximately 100 times that at ground level.

The above figures should be reduced by approximately 10% due to shielding by building structures. The 10% figure has been taken as an average for the whole U.S. population and should not be too different for Ontario residents.

As previously mentioned, part of the radiation exposure to man is caused by cosmogenic radionuclides. These are produced by the interaction of cosmic radiation with atmospheric gases. The four cosmogenic radionuclides that contribute a calculable, but small, dose to man are carbon-14, tritium (hydrogen-3), sodium-22 and beryllium-7. The average whole body dose from these is less than 1 mrem/y (4), and is essentially all from the incorporation of carbon-14 into the body chemistry.

The concentrations of some of the naturally produced cosmogenic radionuclides have been greatly influenced by nuclear weapons testings. This source of radiation exposure will be discussed in section 2.5.

(iv) Terrestrial Radiation Exposure

A significant source of man's exposure is from the naturally occurring primordial radionuclides, i.e. those radionuclides which were present at the formation of the earth. The magnitude of this exposure is relatively uniform and is similar to that due to cosmic radiation. The terrestrial radionuclides which contribute to man's exposure are series radionuclides from the radioactive decay chains of uranium-238 and thorium-232 and the non-series radionuclides, potassium-40 and rubidium-87, which decay directly to stable nuclides. A third decay chain headed by uranium-235 is not a significant source of natural radiation exposure because of its relatively low occurrence, about 0.7 percent of natural uranium.

These radionuclides contribute an average of 58 mrem/y to the total of 102 mrem/y of natural radiation exposure in the U.S.(4). This is composed of 40 mrem/y external and 18 mrem/y internal exposure.

The concentration of the primordial radionuclides in the soil is determined by the processes and rock type from which it is formed. Igneous rocks, which comprise about 90% of the earth's crust, generally have more radioactivity than sedimentary and metamorphic rocks. However, 75% of the earth's surface is covered by sedimentary rocks.

External Exposure from Terrestrial Radioactivity

The radiation that causes the largest increment of external terrestrial exposure is generally gamma radiation. Table 2.1 gives the radionuclide content and dose rates from common rocks and soils due to gamma radiation (1). It can be seen that the thorium-232 decay chain and potassium-40 each contribute about 40% of the dose rate at 1 metre above the ground and the uranium-238 chain contributes about 20%. The beta and alpha radiation due to these sources is generally neglected although in special cases, the beta radiation could cause significant skin exposure, e.g. people living on earthen floors.

In the United States, the average population dose from these sources is 55 mrem/y (range of 30 - 95 mrem/y) with potassium-40, the uranium-238 series and the thorium-232 series contributing about 17, 13 and 25 mrem, respectively. In Ontario, external exposure is approximately 45 mrem/y at Windsor and Ottawa and 70 mrem/y in Thunder Bay (6). Radon-222 daughters in the uranium-238 chain cause most of the variation in this exposure at a given location because of the highly variable radon air concentrations. However, they generally only contribute less than 10% to the total external exposure and usually less than 5% (1). The ambient radon concentrations are influenced by soil moisture, snow cover and housing. Combining all factors, it has been estimated that indoor living reduces the U.S. population external exposure from terrestrial natural background sources by 20% (1). However, it may increase internal exposure due to the build-up of radon daughters (see next section).

Internal Exposure from Terrestrial Radioactivity

The principal natural sources of internal radiation exposure are shown in Table 2.2 (2). Radionuclides enter the body by ingestion and inhalation. Inhalation is of secondary importance except possibly for radon daughters in areas of high natural uranium concentrations.

Potassium-40 is by far the largest naturally-occurring source of internal radiation. It enters the body mainly in foodstuffs but since it is an essential element, variations in dietary composition have little effect on the body content or on the radiation dose received. The estimated annual average dose from internal potassium-40 is 16 mrem(2).

Rubidium-87 is chemically similar to potassium but it appears in much lower concentrations in the body. This results in doses about 2 orders of magnitude lower than for potassium-40.

The contributions of uranium, radium-226, radium-228 and lead-210 from various foodstuffs to a "standard" dietary intake are shown in Table 2.3 (4). The polonium-210 intake is generally 1.3 times that of lead-210 in the diet. The absorbed dose from these nuclides is very small compared to potassium-40 (see Table 2.2). The major variation in these intakes is due to radium-226 concentrations in drinking water which, in some areas of the United States, may add 1 to 90 pCi/d to the 1.4 pCi/d average (4).

TABLE 2.1

RADIONUCLIDE CONTENT AND DOSE EQUIVALENT RATES FROM COMMON ROCKS AND SOIL (1)

Rock	Uranium ppm	Uranium (mrem/y)	Thorium ppm	Thorium (mrem/y)	Potassium-40 ppm	Potassium-40 (mrem/y)	Total (mrem/y)
Igneous							
Basic	0.9	5.2	2.7	7.3	1.2	14.7	27.2
Silicic (granite)	4.7	26.9	20.0	53.8	5.0	61.3	142.0
Sedimentary							
Shale	3.7	21.2	12.0	32.3	3.2	39.2	92.7
Sandstone	0.45	2.6	1.7	4.6	1.1	13.5	20.7
Limestone	2.2	12.6	1.7	4.6	0.32	3.9	21.1
Upper crustal average	2.8	16.0	10.0	26.9	2.4	29.4	72.3
U.S. surficial average	1.8	10.3	9.0	24.2	1.8	21.8	56.3

Conversion from ppm to mrem/y: uranium, 5.73; thorium, 2.69; potassium-40, 12.3.

TABLE 2.2

ESTIMATED AVERAGE ANNUAL INTERNAL RADIATION DOSES PER PERSON FROM NATURAL RADIOACTIVITY IN THE UNITED STATES (2)

Radionuclide Reference	Dose to whole body			Dose to endosteal cells		Dose to bone marrow			Dose to gonads	
	(1) mrem	(2) mrad	(8) mrem	(2) mrad	(8) mrem	(1) mrem	(2) mrad	(8) mrem	(1) mrem	(2) mrad
K-40	16	19 (a)	17	6	8	16	15	15	16 (b)	19
H-3			0.004	0.001	0.004		0.001	0.004		0.001
C-14			1.0	0.8	1.6		0.7	1.6		0.7
Rb-87		0.6	0.6	0.4	0.4		0.6	0.6		0.3
Po-210 (c)	2		3.0	4.0	21	2	0.3	3.0	2	0.6
Rn-220 (d)							0.05			0.003
Rn-222 (c)			3.0	0.04	3.0		0.08	3.0		0.07
Ra-226 (c)				1.6	6.1		0.1	0.3		0.02
Ra-228 (d)				1.9	7		0.1	0.3		0.03
U-238 (c)				0.8			0.06			0.03
Total	18	21	25	16	47	18	17	24	18	21

(a) 17 mrad/y from beta and 2 mrad/y from gamma
(b) Average: 19 mrem/y, male and 13 mrem/y, female
(c) Uranium-238 series
(d) Thorium-232 series

TABLE 2.3

MEAN LEVELS OF DAILY DIETARY INTAKE pCi/d (4)

City	Uranium	Ra-226	Ra-228	Pb-210	Po-210
New York	0.9	1.8	1.2	1.3	
Chicago	0.9	2.1		1.6 1.3	1.8
San Francisco	0.9	0.8	1.0		
San Juan, Puerto Rico		0.7			
Boston				1.5	
New Orleans				1.6	
Los Angeles				1.3	
Palmer, Alaska				1.4	
Honolulu, Hawaii				1.4	
Mean	0.9	1.4	1.1	1.4	(1.8)

The major contribution to man's exposure from inhaled radioactivity is due to the gaseous elements radon and thoron, and their solid daughter products. Radon-222, in particular, is a prime cause of technically enhanced natural radiation from uranium mill tailings (2). Radon-222, the daughter of the alpha decay of radium-226, is an inert gas having a half-life of 3.8 days. Similarly, radon-220 ("thoron" historically) is the daughter of radium-224 in the thorium-232 chain and has a half-life of 55 s. These gases diffuse from the soil and into the atmosphere. The atmospheric concentrations of these gases and their daughter products depend on many geological and meteorological factors. The greatest dose to man from airborne radioactivity arises from the daughter products of radon. These products become attached to air particulates which upon inhalation are deposited in the lung. It has been estimated from a U.S. study of the health effects from radon in natural gas (7) that natural radon may cause up to 7% of normal lung cancer mortalities in the U.S.

Outdoor radon concentrations vary from approximately 0 to 1 pCi/l. Indoor concentrations tend to be higher particularly in buildings constructed of concrete and gypsum blocks which often contain radium-226, the parent of radon. Indoor concentrations of radon daughter products are a potential concern in areas with high uranium concentrations.

References - Natural Sources

1. Oakley, Donald T., "Natural Radiation Exposure in the United States. ORP/S10 72-1, U.S. EPA, Office of Radiation Programs, Washington, D.C.: 1972.

2. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological Quality of the environment in the United States, 1977". EPA-520/ 1-77-009. September 1977.

3. U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The effects on populations of exposure to low levels of ionizing radiation." Washington, D.C.: National Academy of Sciences, 1972.

4. U.S. National Council on Radiation Protection and Measurements. "Natural Background radiation in the United States. NCRP report no. 45. Washington, D.C.: NCRP, 1975.

5. Rothschild, H.C., "A Criteria Digest on radioactivity in the environment". National Research Council Canada no. 13566. Ottawa: National Research Council Canada, 1973.

6. Canada, Department of National Health and Welfare, Health Protection Branch. "Environmental radioactivity in Canada, January - March 1977." Radiological Monitoring Quarterly Report. Ottawa: Dept. of National Health and Welfare, 1977.

7. U.S. Environmental Protection Agency, Office of Radiation Programs, "Assessment of Potential Radiological Health Effects from Radon In Natural Gas", EPA-520/1-73-004, 1973.

8. Klement, A.W., C.P. Miller, R.P. Minx, and B. Shleien. "Estimates of ionizing radiation doses in the United States": 1960-2000, ORP/CSD 72-1. U.S. Environmental Protection Agency, Office of Radiation Programs, Washington, D.C. (August 1972).

2.2 Nuclear Fuel Cycle

2.2.1 Uranium Mining and Milling

(i) Introduction

There are four uranium mine/mill complexes currently in operation in Ontario. The two operations in Elliot Lake (Denison Mines Ltd. and Rio Algom Ltd.) are currently expanding. The other two complexes are Agnew Lake Mines Ltd., near Espanola, and Madawaska Mines Ltd., near Bancroft, a rehabilitated facility. A fifth complex owned by Rio Algom (Panel Mine, Elliot Lake) is also being rehabilitated. The location of these mining activities is given in Figure 2.1. Table 2.4 summarizes current production capacity and ore characteristics of the four operating complexes.

The techniques used to recover uranium are basically the same for three of the four operating mines. Emission sources for these three mines are therefore similar. Kerr Addison's Agnew Lake Mine has sufficiently different ore mineralogy to allow a variation in mining and milling techniques. At this mine, heap leaching is employed, and only 25% of the ore is processed above ground. The other 75% of uranium extraction takes place within the mine. As a result, hoisting requirements are greatly reduced. Grinding of the ore is not necessary and the acid used for leaching is provided by bacterial oxidation of pyrite contained in the ore. It is therefore expected that process discharges of dust and radon gas will be less than from the model mine/mill complex described on the following pages.

(ii) Model Mine/Mill Complex

A schematic diagram of the model complex is provided in Figure 2.2. For the purpose of estimating radioactive emissions, it is necessary to quantify production rates and characterize the primary constituents of the ore body. For the purpose of this report, the model complex is characterized as follows:

Production Rate :	5000 MTPD (metric tons/day) Ore processed
Ore Characteristics :	1 kg U_3O_8/metric ton recovered; 4:1 ratio U/Th by weight secular equilibrium of the radioactive isotopes
Water Use :	125 l/s
U_3O_8 recovery efficiency :	95 %

Ventilation Air Underground :	10 metric tons of fresh air per metric ton of ore hoisted.

A general description of the operations used to recover uranium, and the radioactive emissions are described below.

(iii) Mining

Every mining operation is unique. Major variations from mine to mine are to be expected because ore bodies differ from one location to another. However, the detailed methods used to mine and transport uranium to the surface are not particularly important in determining overall radioactive emissions.

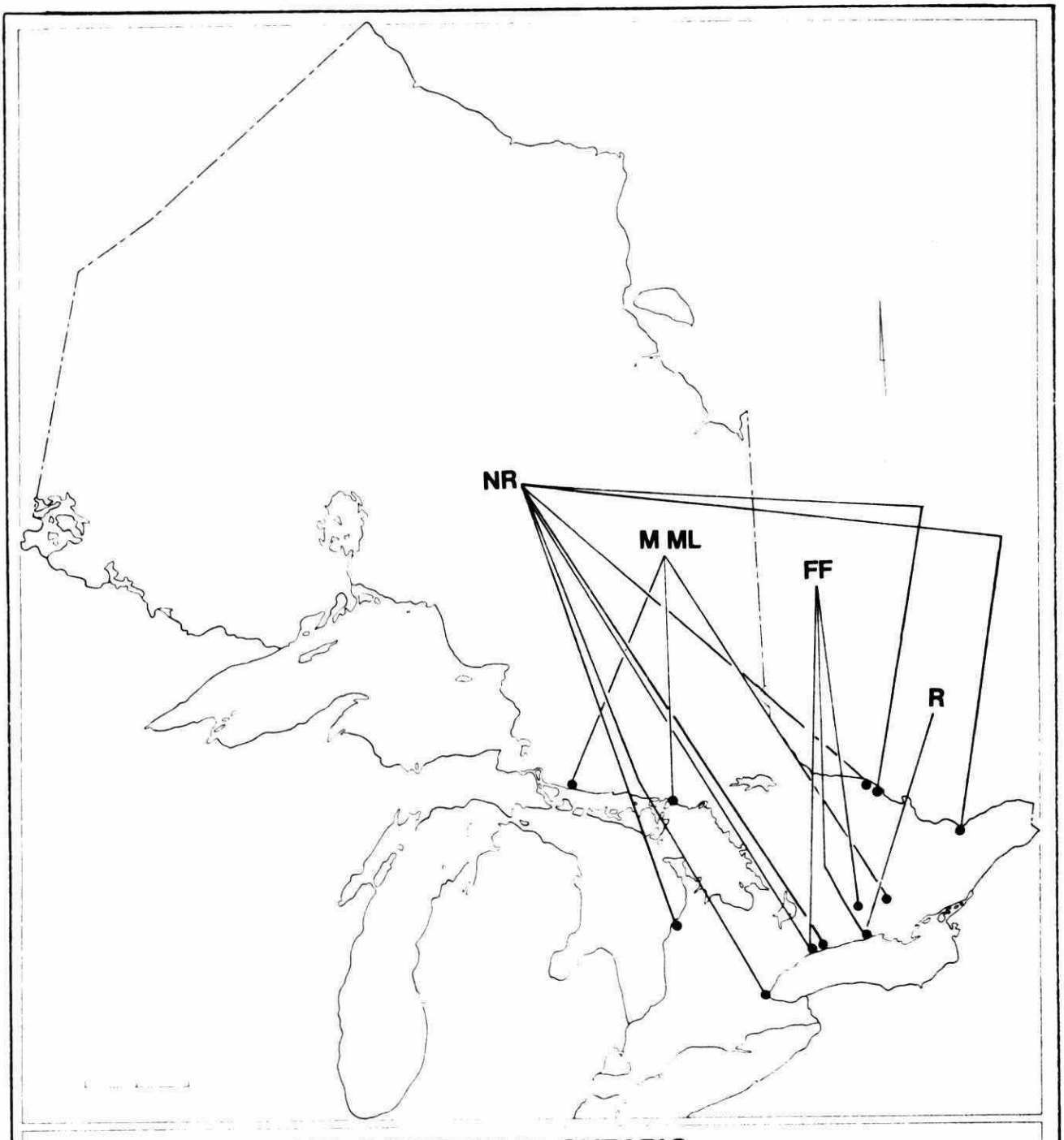
For the purpose of a model mine, the following mining steps are considered: drilling, blasting, transportation of the ore through stopes by load-haul dump vehicles or shuttle cars to boxholes and chutes. The ore is then loaded into trains, crushed underground, hoisted to the surface in a skip, crushed again and transported to the mill for uranium extraction.

Each ore processing operation detailed above generates dust particles and allows the release of radon gas. The dust particles contain radionuclides such as uranium, thorium, radium and lead. In order to minimize the release of these radionuclides to the environment and to protect workers from exposure, water sprays are used in the mine. The sprays are used in all areas where there is high dust generating capacity. The water is used only once in the mine. After use it is collected in sumps and pumped to the mill for treatment and use within the milling process. Excess treated mine water is sometimes pumped directly to the tailings basin where it is eventually treated for radium removal before discharge.

Ventilation practices in uranium mines are designed to minimize internal radiation exposure. The optimum design practice is a once through air system whereby air is directed for one pass through a particular stope before being exhausted. Another procedure is to provide auxiliary ventilation directly to the faces of working stopes and to other parts of the mine as required. Much larger quantities of air are used in uranium mines than in other mining operations.

Since the water sprays cannot be 100% efficient, the ventilation air picks up some radioactive dust, aerosols and radon gas. These are emitted via the exhaust raises to the environment. In some cases the air is filtered to remove particulates before recycle or exhaust. Figure 2.3 indicates the nature of the radioactive emissions from the

Figure
2.1



THE NUCLEAR FUEL INDUSTRY IN ONTARIO

URANIUM MINES (M) MILLS (ML)

Denison Mines- Elliot Lake
Rio Algom- Elliot Lake
Agnew Lake Mines- Agnew Lake
Madawaska Mines- Bancroft

URANIUM REFINERY (R)

Eldorado Nuclear Ltd.- Port Hope

FUEL FABRICATION (FF)

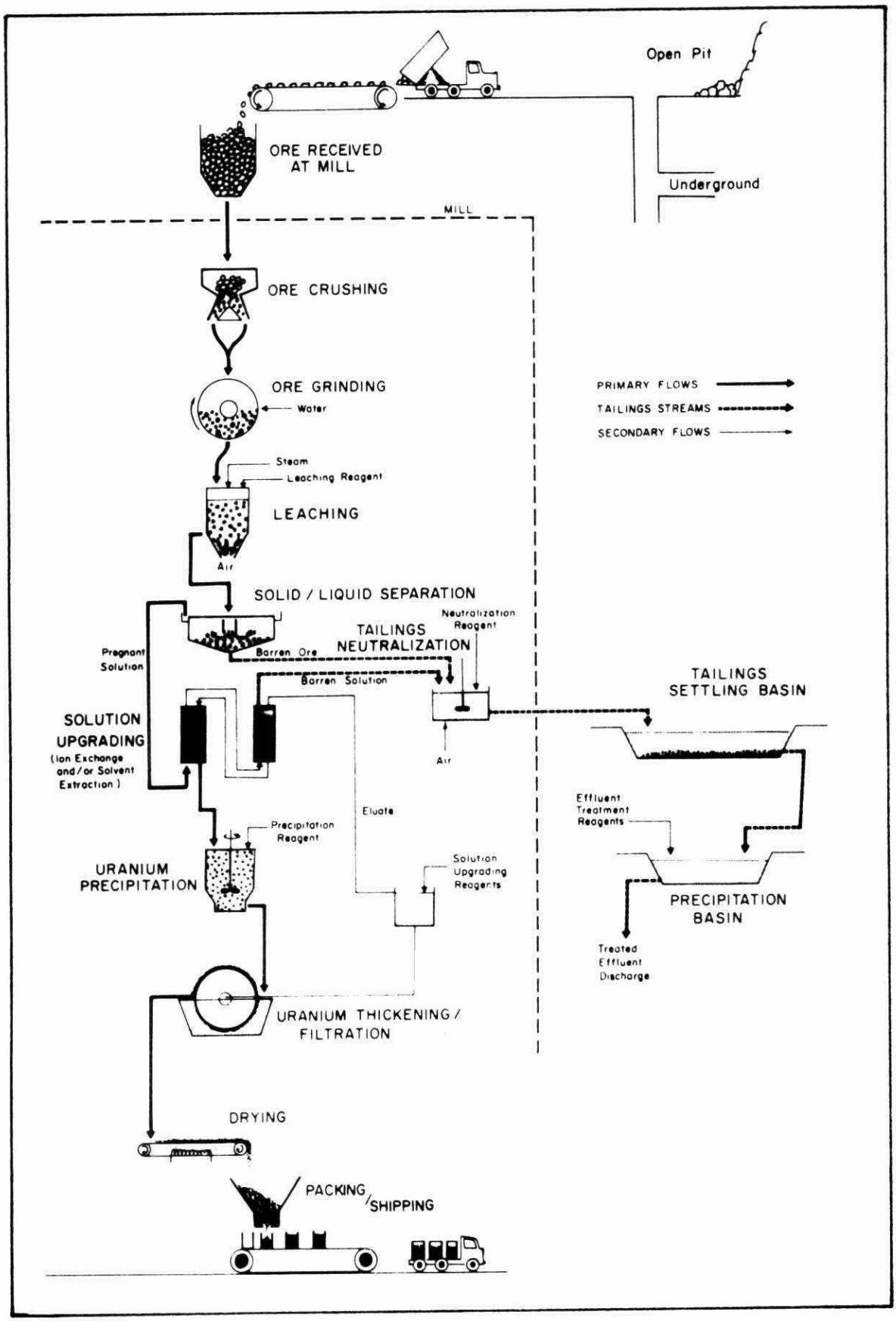
CGE- Toronto
CGE- Peterborough
Westinghouse- Port Hope

NUCLEAR REACTORS (NR)

AECL- Ottawa (Slow poke)
AECL- Chalk River
Ontario Hydro- Pickering
Ontario Hydro- Douglas Point
NPD- Rolpton
McMaster University- Hamilton
University of Toronto (Slow poke)
Ontario Hydro - Bruce

MODEL MILL PROCESS SCHEMATIC

Figure 2.2



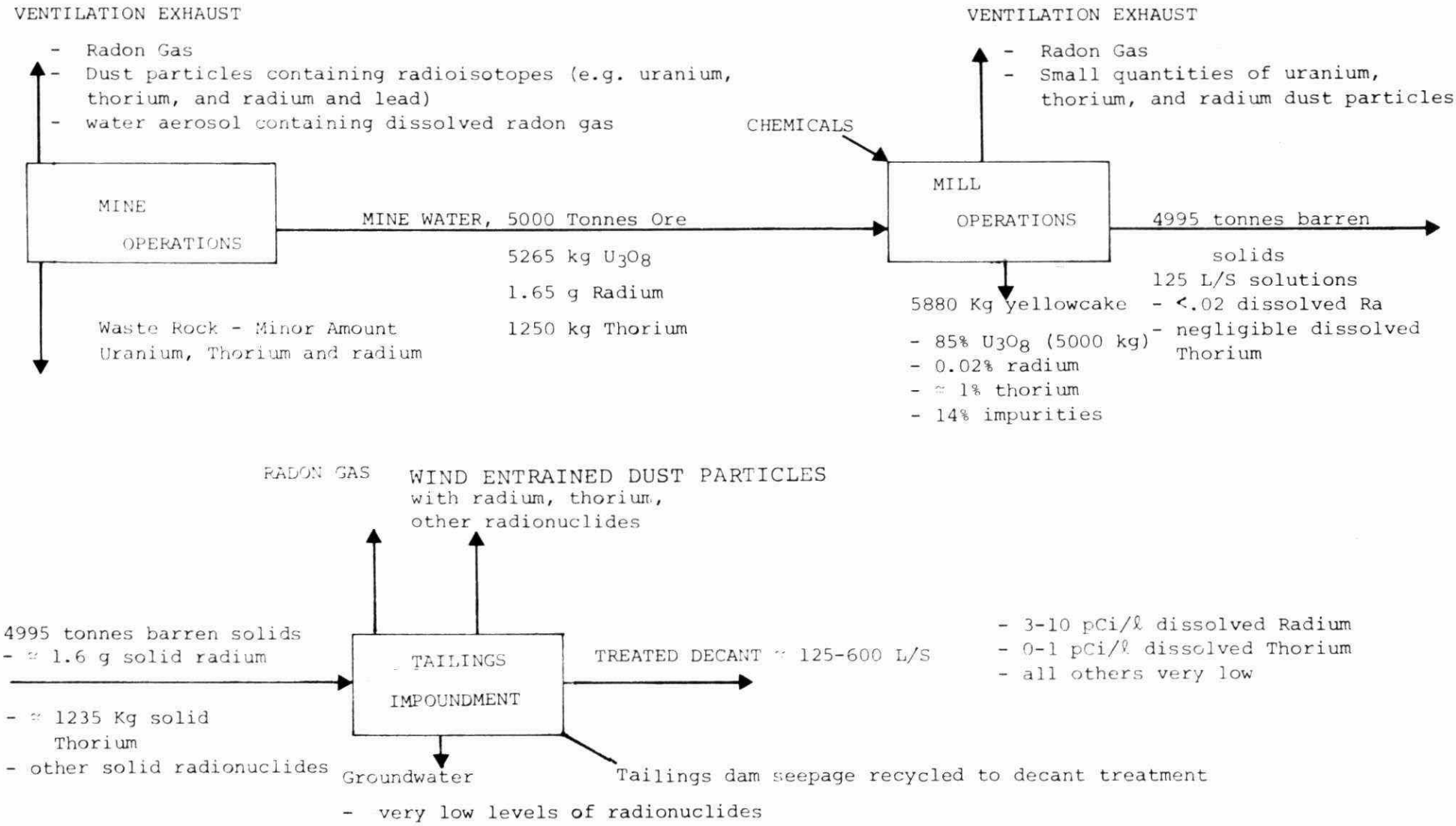

VENTILATION EXHAUST
- Radon Gas
- Dust particles containing radioisotopes (e.g. uranium, thorium, and radium and lead)
- water aerosol containing dissolved radon gas
MINE OPERATIONS
Waste Rock - Minor Amount Uranium, Thorium and radium
MINE WATER, 5000 Tonnes Ore
5265 kg U_3O_8
1.65 g Radium
1250 kg Thorium
CHEMICALS
VENTILATION EXHAUST
- Radon Gas
- Small quantities of uranium, thorium, and radium dust particles
MILL OPERATIONS
5880 Kg yellowcake
- 85% U_3O_8 (5000 kg)
- 0.02% radium
- ≈ 1% thorium
- 14% impurities
4995 tonnes barren solids
125 L/S solutions
- <.02 dissolved Ra
- negligible dissolved Thorium
RADON GAS
WIND ENTRAINED DUST PARTICLES with radium, thorium, other radionuclides
4995 tonnes barren solids
- ≈ 1.6 g solid radium
- ≈ 1235 Kg solid Thorium
- other solid radionuclides
TAILINGS IMPOUNDMENT
TREATED DECANT ≈ 125-600 L/S
- 3-10 pCi/ℓ dissolved Radium
- 0-1 pCi/ℓ dissolved Thorium
- all others very low
Groundwater
- very low levels of radionuclides
Tailings dam seepage recycled to decant treatment

Figure 2.3 **MODEL MINE/ MILL / TAILINGS COMPLEX 5000 MTPD**

TABLE 2.4

PRODUCTION CAPACITY/ORE CHARACTERISTICS FOR ONTARIO URANIUM MINE/MILLS

	Agnew Lake Mines	Denison Mines	Madawaska Mines	Rio Algom Mines
Production Data:	- Start-up 2nd quarter 1977, - Expect to produce 1 million lbs. U_3O_8 per year	- Processed 6000 tons/day (TPD) in 1976 yielding 3,112,000 lbs. U_3O_8/y - Mill capacity 7000 TPD	- Resumed production in August 1976 at 750-800 TPD - Mill capacity 1,500 TPD	- Processed 4,574 TPD in 1976 yielding 4,483,000 lbs. U_3O_8/y - Mill capacity to 7,000 TPD in 1978 - Panel mill to be re-activated in 1980 at 3,300 TPD
Ore Characteristics:				
U_3O_8 (lb/ton)	1.07 - 1.5	2.2	1.85 - 2.9	2.0 - 2.8
ThO_2 (lb/ton)	4.5	1.0	1.0	0.7
Y_2O_3 (%)	ND	0.01	Trace	0.02
Rare Earths (%)	ND	0.06	Trace	-
S (%)	ND	4	ND	3.5
Fe (%)	ND	3	ND	3
Heavy Metals (%)	ND	Trace	ND	Trace
SiO_2 (%)	> 80	60 - 85	10	60 - 85

ND = No data.

mine. Particulate radon releases from a model mine, to support a 5000 MTPD mill, have been estimated from Elliot Lake studies (1). Particulate releases of <1 g/s and radon releases of about 60 μCi/s have been estimated.

(iv) Milling

For the purpose of a model mill, there are four basic operations common to all milling operations: ore preparation, uranium dissolution, uranium concentration and product recovery. The major differences in uranium milling procedures used in Ontario may be attributed to the chemicals used in the processes (Table 2.5). A general description of these operations is given below.

Ore Preparation

Uranium mill processing is a hydrometallurgical operation in which uranium is dissolved from the ore by using an acid or a base. To obtain high uranium recoveries, the ore must be crushed and ground to expose the uranium minerals for the leaching reaction. This usually involves further crushing of the ore received from the mine, followed by a fine wet grinding operation. Each ore body has an optimum size requirement which is determined by the ore mineralogy. After grinding, the ore is dewatered (~ 80% solids) and sent on to leaching.

The ore preparation operations are major sources of dust and radon gas emanations. The dust and radon are discharged to the environment via the building ventilation exhaust after baghouse dust control. From Elliot Lake studies, particulate emissions of about 0.33 g/s and radon release of <2 μCi/s have been estimated for a 5000 MTPD mill facility.

Uranium Dissolution (Leaching)

From the point of view of environmental concerns this may be the most important milling operation. The process dissolves the uranium from the parent ore. The operation is carried out in large mixed vessels (pachucas) containing the ore slurry. Air and steam are bubbled from the bottom of the vessel to promote mixing, oxidizing conditions and to raise the temperature of the slurry. Sulphuric acid is used to lower the pH and dissolve the uranium. Several chemical reactions take place in the pachucas, and other elements are dissolved in addition to the uranium.

Once the uranium is dissolved, the now barren solids are separated from the loaded or pregnant solution by filters or thickeners. The solids are washed during this operation with fresh water and/or recycled barren solution and sent to tailings neutralization. After pH adjustment and clarification, the pregnant solution is sent to uranium concentration.

In the acid-leach process, it is believed that less than 1% of the radium in the ore is solubilized. The amount of dissolved thorium is dependent on the ore mineralogy, but can reach high levels (e.g. 60% solubilization). The dissolved portions of these radionuclides are carried over to uranium concentration. The remaining solid portions are discharged, after solids neutralization, to the tailings area.

Radon gas and dust emissions from the leaching pachucas are responsible for the greatest fraction of mill ventilation air emissions to the environment. Emission estimates for all remaining mill sources beyond the ore preparation step have been aggregated, and are presented at the end of this section.

Uranium Concentration (Ion Exchange)

Uranium concentration is carried out by a process called ion exchange. The pregnant solution is pumped through a series of columns containing an ion exchange resin. The resin is highly selective for uranium, and exchanges ions on the resin surface for uranium ions in solution. Very few other dissolved ions are picked up by the resin. The barren solution (stripped of its uranium content) is recycled to barren ore washing and eventually discharged to tailings neutralization.

After the columns are loaded to their optimum capacity a second solution (eluant) is pumped through the columns to recover the uranium. Only small quantities of eluant are required to recover the uranium and a 10 to 20 fold increase in dissolved uranium concentration is achieved. The loaded eluant (eluate) is then prepared for uranium recovery by pH adjustment and, simultaneously, minor contaminant removal.

Solvent-extraction can also be used to concentrate the uranium. The basic process is the same, however, rather than using a solid ion exchange resin, a liquid solvent is used.

Uranium concentration is not a direct source of emissions. It is worth noting, however, that the resin is highly selective for uranium. Other radionuclides such as thorium radium and lead-210 are rejected. These radionuclides become part of the barren liquor which is eventually discharged from the mill in solid and liquid form. Typical yellowcake analyses indicate that only 0.02 percent of the radium and approximately 1 percent of the thorium are not rejected, and remain in the yellowcake product.

Product Recovery (Precipitation)

Uranium is recovered from solution with the addition of a base to raise the pH to 7-7.2. The precipitated uranium product, called yellowcake, contains approximately 85 percent by weight U_3O_8. Yellowcake is separated from solution by thickening and filtration. After drying, the yellowcake is packaged in drums and is ready for shipment to the uranium refineries.

TABLE 2.5

URANIUM MILLS IN OPERATION IN ONTARIO

Company	Nominal Mill Capacity, Ore	Leaching Reagents	Solution Upgrading		Uranium Precipitating Reagents
			Methods	Reagents	
Agnew Lake Mines Limited	n/a	H_2SO_4, $Fe_2(SO_4)_3$	CIX-SX	H_2SO_4, NH_3	NH_3
Denison Mines Limited	7000 tons/day	H_2SO_4, $NaClO_3$	IX	HNO_3	NH_3
Madawaska Mines Limited	1500 tons/day	H_2SO_4, $NaClO_3$	IX	NaCl, H_2SO_4	MgO
Rio Algom Limited	7000 tons/day	H_2SO_4	IX	HNO_3	NH_3

NOTES:

CIX - continuous ion exchange
IX - column ion exchange
n/a - solvent extraction

H_2SO_4 - sulphuric acid
$NaClO_3$ - sodium chlorate
$Fe_2(SO_4)_3$ - ferric sulphate
NH_3 - ammonia

HNO_3 - nitric acid
NaCl - sodium chloride
MgO - magnesium oxide

Emissions from this operation are relatively minor and consist primarily of dust from the yellowcake drying plant. Entrained dust particles, which are primarily U_3O_8, will exist with the ventilation exhaust to the environment after scrubber and baghouse dust control. As previously indicated, emission rates for all mill airborne sources have been aggregated. For a model 5000 MTPD mill, particulate emissions of <0.2 g/s and radon release rates of about 4 μCi/s have been estimated.

Tailings Treatment and Storage

After solid/liquid separation of the barren solids (tails) from the pregnant solution, the tails are washed to recover any entrained uranium. The tails and accompanying barren solutions are then neutralized (to pH 10.5) by the addition of a lime slurry. The tailings slurry is then disposed in an area which provides for containment of the solids. Liquid discharges (decant) from the tailings area are treated by pH adjustment (to pH 7) and barium chloride addition to control dissolved radium levels. After radium precipitation, the decant is discharged to the receiving stream.

The barren solution sent to tailings neutralization contains dissolved radium, thorium, lead-210 and uranium. Neutralization precipitates thorium, lead-210 and uranium to very low levels. Present treatment practice for the removal of radium from tailings pond effluent consists of the addition of barium chloride. Radium, which is chemically similar to barium, co-precipitates with barium in the form of a barium-radium sulphate. Dissolved radium levels in the final tailings effluent are normally on the order of 3-10 pCi/l, while dissolved thorium is on the order of 0-1 pCi/l.

Of the approximately 5000 tonnes of barren solids discharged to the tailings area from the 5000 MTPD model mill, only 1.6 grams of radium and 1200 kg of thorium are discharged. These compounds as well as the remaining solid radionuclides remain in solid form unless acid seepage and runoff are encountered. This will not occur in an operating complex using neutralization procedures.

The two major airborne emissions from tailings areas are radon gas and wind entrained dust particles. At the present time, the mining companies and various government agencies are sponsoring extensive research into waste management techniques. The results of these studies are not yet available.

References - Mining and Milling

1. James F. MacLaren Ltd., "Environmental Assessment of the Proposed Elliot Lake Uranium Mines Expansion Volume I: Background Information", March, 1977.

2. James F. MacLaren Ltd., "Environmental Assessment of the Proposed Elliot Lake Uranium Mines Expansion Volume 2: Background Information Update", February 1978.

2.2.2 Uranium Refinery

(i) Introduction

There is currently only one uranium refinery in Canada, located in Port Hope, Ontario. This refinery is operated by Eldorado Nuclear Ltd., and can be segregated into a number of distinct circuits:

Uranium Trioxide (UO_3) Circuit	- All yellowcake received at the refinery is treated in the UO_3 circuit for purification.
Uranium Hexafluoride (UF_6) Circuit	- Uranium destined for export is converted from UO_3 to UF_6.
Uranium Dioxide (UO_2) Circuit	- Uranium destined for CANDU fuel is converted from uranyl nitrate (UO_3 circuit intermediate) to ceramic grade UO_2.
Uranium Metal Circuit	- Specialty castings of uranium metal are produced from UF_4, a UF_6 circuit intermediate.

These circuits are shown schematically in Figure 2.4

The existing refinery has a design capacity of 5,500 metric tons/y of uranium (MTU) for UO_3 production. The UF_6 circuit has a capacity to produce 4,500 MTU/y of UF_6 from UO_3. In addition, Eldorado proposes to construct a new UO_3/UF_6 refinery in Ontario in the near future. This new facility would be capable of producing 9,000 MTU/y of UF_6.

Emission estimates for this report are based on the environmental impact assessment prepared for Eldorado's new facility (1,2) and are scaled for a model facility processing 5,000 MTU/y UO_3 and subsequently 4,000 MTU/ y UF_6 and 1,000 MTU/y UO_2.

(ii) UO_3 Plant

In order to process 5,000 metric tons of uranium to either UF_6, ceramic grade UO_2, or U metal, the refinery must handle approximately 7,100 metric tons of ammonium diuranate yellowcake received in 45 gallon steel drums. This yellowcake contains the following major radionuclides:

Parameter	% on Total Sample Basis
Uranium-Natural	Average 70.8% (Range 65-75%)
Thorium-232	Average 0.71% (Range 0.21-1.42%)
Radium-226	Average 150 pCi/g (Range 20-400 pCi/g)

Other principal constituents include H_2O, SO_4, NH_4, NO_3 and oxygen which is combined with the uranium. The main steps in the UO_3 process include: Warehousing and Sampling, Yellowcake Preparation, Digestion, Solvent Extraction, Evaporation, and Denitration.

Warehousing and Sampling/Yellowcake Preparation

Upon arrival at the refinery, the yellowcake is weighed, sampled, analysed for uranium and impurity content, then treated prior to digestion. Feed transfer points and hoppers have baghouse dust control and will generate an emission load of about 78 gU/h yellowcake particulate for a model 5,000 MTU/y circuit capacity. Yellowcake preparation dusts are controlled by a series of sintered metal filters and will generate an emission load of about 8 gU/h yellowcake particulate.

In addition to yellowcake particulate losses, radon gas will be released at these sources. The yellowcake as received at the plant will contain the equilibrium radon content. The release of the full complement of radon to the atmosphere during sampling would result in a discharge of approximately 140 μCi/h. If the sampled yellowcake is stored prior to entry into the process, the radon could grow back. Thus the yellowcake preparation step could result in an additional release of up to 140 μCi/h.

Digestion

Prepared yellowcake is fed into a series of digestors. Nitric acid is added to these agitated tanks to dissolve the yellowcake forming a solution of uranyl nitrate, dissolved impurities, and residual undissolved silica. Digestor vents are scrubbed in a nitric acid recovery system (absorber and concentrator) to recover NO_x and entrained HNO_3 and does not give rise to airborne uranium loss. There are no aqueous waste discharges from this operation.

Solvent Extraction

The impure uranyl nitrate solution from digestion is contacted with a solution of tributyl phosphate and kerosene in extraction columns. The uranium is extracted into the organic phase, leaving the impurities in the aqueous solution (raffinate phase). The organic, uranium bearing phase is then contacted with a stream of recycled water, thereby re-extracting the uranyl nitrate into a second aqueous phase. The barren solvent is then treated prior to recycle.

The impurities contained in the raffinate phase are recovered by evaporation and drying. The collected vapours are recycled as process water make-up or by way of the nitric acid recovery system. The final solids stream or raffinate solids contain the yellowcake impurities in a concentrated form for licensed waste management. For a model 5,000 MTU/y refinery, this raffinate waste will be produced at a rate of about

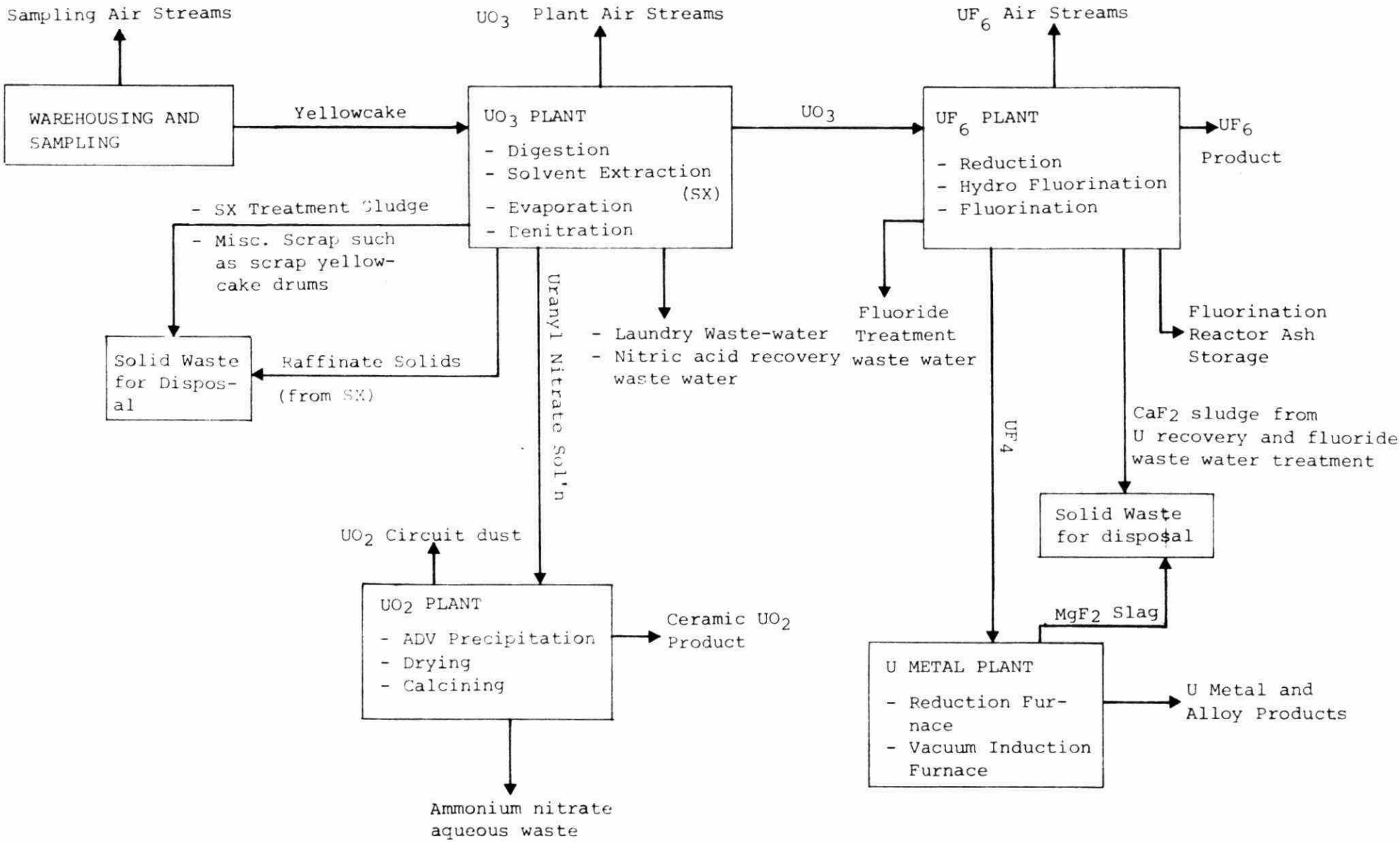


Figure 2.4 **URANIUM REFINERY- SCHEMATIC SHOWING PLANT EMISSION POINTS**

120 kg/h dry solids containing 0.15 kg uranium/h, 6.7 kg thorium-232/h, and 2,400 pCi radium-226/g dry solids. The raffinate solids contain virtually all of the radium and thorium which enter the circuit as yellowcake impurities. An additional small solid waste stream is generated from solvent treatment, containing some fine silicate sand and potentially a trace of uranium.

Since the radium is removed from the circuit at this point, radon releases are not a factor in subsequent process steps. The circuit inventory between feed preparation and raffinate treatment is estimated to be 3 days' production. Assuming that one half of the radon being generated in these process steps is ultimately released to the atmosphere, an additional 40 μCi/h of radon will be released. This estimate is based on analysis provided in Reference 1.

Evaporation/Denitration

Purified uranyl nitrate solution from solvent extraction is concentrated in a staged evaporation process. Vapours are condensed for recycle as process water. The evaporation step does not generate any emission streams. The concentrated aqueous uranyl nitrate solution is then either forwarded to the ceramic UO_2 circuit, or on to the denitration stage where, by heating, remaining nitric acid and nitrates are removed leaving a dry, yellow UO_3 powder. The vapour phase from the denitration operation is passed through a fume condenser, the nitric acid recovery system, and finally a catalytic converter to control NO_x losses. No radioactive emissions are expected from this operation.

Auxiliary Operations

There are no appreciable water-borne radioactive discharges. All sumpages and spills which occur in the UO_3 plant are directed to a sump treatment system for uranium recovery. Water discharged from the sump system is directed to the raffinate evaporation stage, and thus is eventually recycled for process water make-up. A bleed stream for the process water recycle system is discharged from the nitric acid recovery system and will not likely contain radionuclides. With the exception of the laundry system, no utility streams generate radioactive emissions. The laundry system could result in a water-borne discharge of up to about 3 gU/h on an intermittent basis.

(iii) UF_6 Plant

Uranium which is destined for LWR nuclear fuel is converted to UF_6, the final chemical conversion step prior to enrichment. The UF_6 process includes the following main steps: Reduction, Hydrofluorination, Fluorination and Product Packaging. In addition, HF recovery and uranium recovery systems are provided.

Reduction

Dry, powdered UO_3 from the UO_3 circuit is initially screened and pulverized prior to reduction. In the reduction reactor, the UO_3 is contacted with dissociated anhydrous ammonia (N_2 and H_2). The resulting UO_2 is then pulverized prior to hydrofluorination. All conveyors and hoppers have baghouse dust control, and UO_3/UO_2 pulverization (preparation) will generate an airborne uranium load of 15 gU/h. The off-gas from the reduction reactor is passed through a sintered metal filter, generating an additional load of 15 gU/h for a 4,000 MTU/y UF_6 circuit. No water-borne or solid waste streams are generated from this step.

Hydrofluorination

Dry UO_2 is converted to UF_4 by reaction with HF. Reactor off-gas, and a gas stream from the subsequent UF_4 preparation step are directed to the HF recovery system. General area sumpage is transferred to the uranium recovery system. Thus, no emission streams are discharged directly from this step.

Fluorination/Product Packaging

Prepared UF_4 is fed to a flame reactor and a clean-up reactor connected in series. Fluorine gas, which is generated from HF in electrolytic cells, is introduced into these reactors to convert solid UF_4 to gaseous UF_6. Two reactors in series are provided to insure optimum fluorine consumption. As the fluorine gas passes through the reactor, it picks up volatile UF_6. The reactor off-gas is filtered to remove residual solids (flame and clean-up reactor ash), and passes through refrigerated cold traps to liquify the UF_6 product before the gas stream is passed to the HF recovery system. The liquid UF_6 from the cold traps is fed into shipping cylinders of either ten or fourteen ton capacity where it is allowed to solidify at room temperature prior to shipment.

UF_4 feed hoppers and transfer points have baghouse dust control, generating an airborne load of approximately 29 gU/h. The recovered reactor ash contains in the order of 5% uranium and 10% thorium. This solid ash (0.8 MT/y) is stored on site for future uranium recovery. The reactor ash will also contain the short-lived uranium daughters such as thorium-234 and protactinium-234.

Auxiliary Systems

In the event of an emergency situation in the fluorination area, or the UF_6 cylinder filling area, normal ventilation could be diverted to a KOH scrubber. An emergency of this sort could lead to a short-term emission of up to 70 gU/h. In this case, scrubber solution would be treated in the uranium recovery system.

The HF recovery system treats air streams from hydrofluorination and fluorination. Residual amounts of uranium will be released from this scrubber system; airborne uranium losses of 0.6 gU/h have been estimated

for this source. Uranium recovered in the scrubber solution will be associated with the recovered HF stream, or possibly a trace amount with an excess water stream generated in this system which is treated in a fluoride wastewater treatment system.

The uranium recovery system provides centralized treatment to recover uranium for recycle from wash waters, emergency ventilation scrubber solution, and UF_6 circuit sumpage. The system generates a CaF_2 solid waste which could possibly be contaminated with a trace of uranium, and also generates a wastewater stream treated in the fluoride treatment system. The fluoride treatment system in turn generates a CaF_2 sludge. Final treated effluent will not likely contain uranium as the high pH conditions resulting from lime treatment should precipitate any uranium loss. The resulting CaF_2 solid waste from fluoride treatment could contain a trace of uranium and thus is combined with the raffinate solids for licensed waste management.

Emission rate estimates for both the UO_3 and UF_6 circuits are summarized in Table 2.6.

(iv) UO_2 Plant

Ceramic grade uranium dioxide is a specially prepared UO_2 which has a high surface area per unit weight, suitable for pelletizing, sintering and subsequent preparation as nuclear fuel for CANDU type reactors. The ammonium diuranate UO_2 process includes the following steps: ADU Precipitation, Filtration, Drying and Calcining.

ADU Precipitation/Filtration

Concentrated uranyl nitrate from the evaporation step in the UO_3 circuit is mixed with ammonium hydroxide, to precipitate ammonium diuranate (ADU). The resulting slurry mixture is dewatered by vacuum filtration, producing a wet cake for drying, and a liquid aqueous waste stream of ammonium nitrate for disposal. This liquid stream will likely contain a trace amount of uranium, but radium contamination is minimized since the radium is essentially completely removed in the UO_3 refining circuit prior to the UO_2 draw-off point.

Drying/Calcining

The wet ADU precipitate (containing entrained ammonium nitrate) is first dried, then thermally decomposed to UO_3 which in turn is reduced to UO_2. The final process is performed in a gas-heated calciner in the presence of H_2 in a manner which is likely similar to the reduction step in the UF_6 circuit. Before shipment, all uranium dioxide is pulverized and blended.

This process sequence will likely generate airborne emission loads from the dryer, calciner, and from pulverizing operations and will involve particulate loads of UO_2 and possibly UO_3.

Emission estimates and control equipment description are not available for a 1,000 MTU ceramic grade UO_2 circuit. In summary, the ammonium diuranate UO_2 process will generate the following waste streams:

- Ammonium nitrate aqueous waste which will contain trace amounts of unrecovered ADU from solid/liquid separation equipment.
- Dust loadings from ADU drying/UO_3 thermal decomposition, UO_2 calcination, and UO_2 pulverization.

It is worth noting that process modifications have been developed by Eldorado in recent years to eliminate the problem of disposing of the aqueous liquid effluent. This other patented process is referred to as the ammonium uranate process.

(v) U Metal

Uranium metal is produced intermittently at the refinery. This process involves the reduction of uranium tetrafluoride from the UF_6 circuit with magnesium. This UF_4/Mg mixture is fed to a reduction furnace in steel reactor vessels. The product of the reaction is an ingot of uranium metal and a magnesium fluoride slag for licensed waste management. The crude ingot is then normally vacuum remelted and cast into billets, or alternatively can be machined as is for special requirements. Castings may be subsequently extruded, forged, rolled, machined, or used as is for various applications. The magnesium fluoride solid waste will contain residual amounts of uranium, and thus requires licensed waste management.

(vi) Waste Management

At present there is extensive research into waste management techniques for low level radioactive waste such as that generated by a nuclear refinery or a uranium mine/mill facility. The situation for waste disposal as opposed to waste storage is unclear. Until such time as these concepts are clearly defined, it is not possible to provide radioactive release estimates for a model waste management facility.

The current thinking of the Atomic Energy Control Board is perhaps reflected in the following excerpts from a statement by Dr. Larry Henry, scientific advisor with the AECB radioactive waste management division, at the Eldorado Nuclear Port Granby hearings on February 9, 1978 (3).

> "The AECB has never entertained an application for a waste management disposal system. Storage has always been the requirement, and retrievability has always been the condition."
>
> "The problem of rad waste disposal as it is being used today, disposal, is now being examined in considerable detail at the federal level. There is a great deal of activity going on and it will continue to go on and we are operating under the assumption that progress at this level will in fact jell with our concept of storage."

TABLE 2.6

Emission Rate Estimates for a UO_3/UF_6 Refinery

A) Model 5,000 MTU/y UO_3 Circuit

1) Airborne yellowcake particulate from yellowcake sampling baghouse dust control: 78 g U/h.

2) Airborne yellowcake particulate from yellowcake preparation sintered metal filter: 8 g U/h.

3) Airborne radon release from the UO_3 circuit: up to 320 μCi/h.

4) Raffinate solid wastes (120 kg/h dry solids) containing: 0.15 kg U/h, 6.7 kg Th-232/h and 2,400 pCi Ra-226/g dry solids.

5) Laundry system waste water: 3 g U/h on an intermittent basis.

B) Model 4,000 MTU/y UF_6 Circuit

1) UO_3/UO_2 particulate from UO_3/UO_2 preparation baghouse dust control: 15 g U/h.

2) UO_3/UO_2 particulate from reduction reactor off-gas sintered metal filter: 15 gU/h.

3) UF_4 particulate from UF_4 preparation baghouse dust control: 29 g U/h.

4) HF recovery fume scrubber off-gas: 0.6 g U/h.

5) Emergency ventilation KOH scrubber off-gas: up to 70 g U/h.

"As a license condition, the AECB requires that licensees meet the requirements of other government agencies insofar as they are not inconsistent with the Atomic Energy Control Act and regulations. This certainly implies that there is judgement required and, in each case, where judgement is required it will be done with the co-operation and in conjunction with the applicable agency. This is a general statement regarding licensing."

References - Uranium Refinery

1. James F. MacLaren Ltd. and Hydrology Consultants Ltd. "Environmental Impact Assessment, the Port Granby Project," prepared for Eldorado Nuclear Ltd. May , 1977.

2. James F. MacLaren Ltd. "Supplement to Environmental Impact Assessment, The Port Granby Project, Responses to Phase 1: Environmental Hearings", November, 1977.

3. Transcripts, Federal Environmental Assessment Board, (Hearings re Eldorado Nuclear Limited Port Granby Proposal), Volume 5, Phase II, February 9, 1978.

2.2.3 Fuel Fabrication

(i) Introduction

The CANDU fuel bundle consists of a varying number of closely spaced elements each of which contain high density natural ceramic grade UO_2 in the form of solid pellets in a thin zircaloy sheath. These elements are held together by end plates and are separated by spacers brazed to the sheaths. For example, a Pickering fuel bundle consists of 28 elements containing a total of 19.7 kg of natural uranium.

The typical fuel fabrication process consists of preparing UO_2 powder by the following series of processes; an initial prepress followed by granulation, final pressing, sintering of the "green pellets", grinding the pellets to the required diameter, washing and air drying the pellets and loading the stacked pellets into zircaloy sheaths in the bundle assembly step. Bundles are inspected and monitored for radiation contamination and then packaged for shipment to CANDU nuclear generating stations. Fuel fabrication plants machine all zircaloy parts used in the bundle assembly but these processes do not involve potential radiation emissions or wastes.

These process steps are described in more detail in the following section. Likely emission source points are identified, however emission estimates and confirmation of these source points are not available at this time.

There are at present two uranium fuel fabricators in Ontario. Westinghouse runs an integrated plant at Port Hope, while Canadian General Electric conducts pellet manufacturing in Toronto and bundle assembly in Peterborough.

(ii) Pellet Manufacture

Pre-Press, Granulation and Final Press

Uranium dioxide powder is received in lot quantities, suitable for planned production rates. After sampling, the powder is pre-pressed at pressures of 550 to 850 kg/cm^2 into wafers or slugs.

After the pre-press, the uranium dioxide slugs are granulated through a fixed size sieve. Granular material is fed into a pellet press where it is pressed at pressures of 2800 to 5600 kg/cm^2 into "green" pellets of predetermined weight, height and diameter. Pellets are sampled and inspected to ensure that they conform to specifications.

Each uranium processing station is provided with a local dust collector exhausting to a central dust collection system.

Sintering

"Green" pellets are placed in molybdenum containers or boats and are continuously stoked through a sintering furnace. Small hydrogen flames at each end of the furnace maintain a reducing atmosphere in the furnace. The peak temperature is 1650° C to 1700° C. Furnace off-gas is collected by exhaust hoods and routed to the air filtration system.

Grinding, Washing and Drying

Sintered pellets are ground on a centreless grinder to the specific diameter required for use in the reactor. Lubricating fluid is sprayed on the pellets continuously to reduce their temperature rise during grinding. Pellets are then washed with a small quantity of hot water to remove the grinding coolant and sludge and they are then air dried.

The lubricant used in the grinding step is recycled through a centrifuge. Solids collected by the centrifuge are returned to the uranium refinery for re-processing. Grinders are equipped with exhaust hoods which collect the air streams for treatment with an impingement type scrubber to remove uranium particulate.

Wash water used to remove excess coolant and sludge from the pellets is transferred to a settling tank/centrifuge system or a leaf filter. The solids are recovered and the stream monitored before being discharged to the sewage system.

(iii) Zircaloy Fabrication

Spacers and Bearing Pads

Zircaloy strip received from suppliers is inspected before being cut into lengths. Zircaloy lengths are then degreased, pickled, washed, vapour blasted, rinsed and dried before being coated on one side with beryllium by a "vacuum deposition" process. Spacers and bearing pads are blanked from these coated lengths of zircaloy.

End Caps

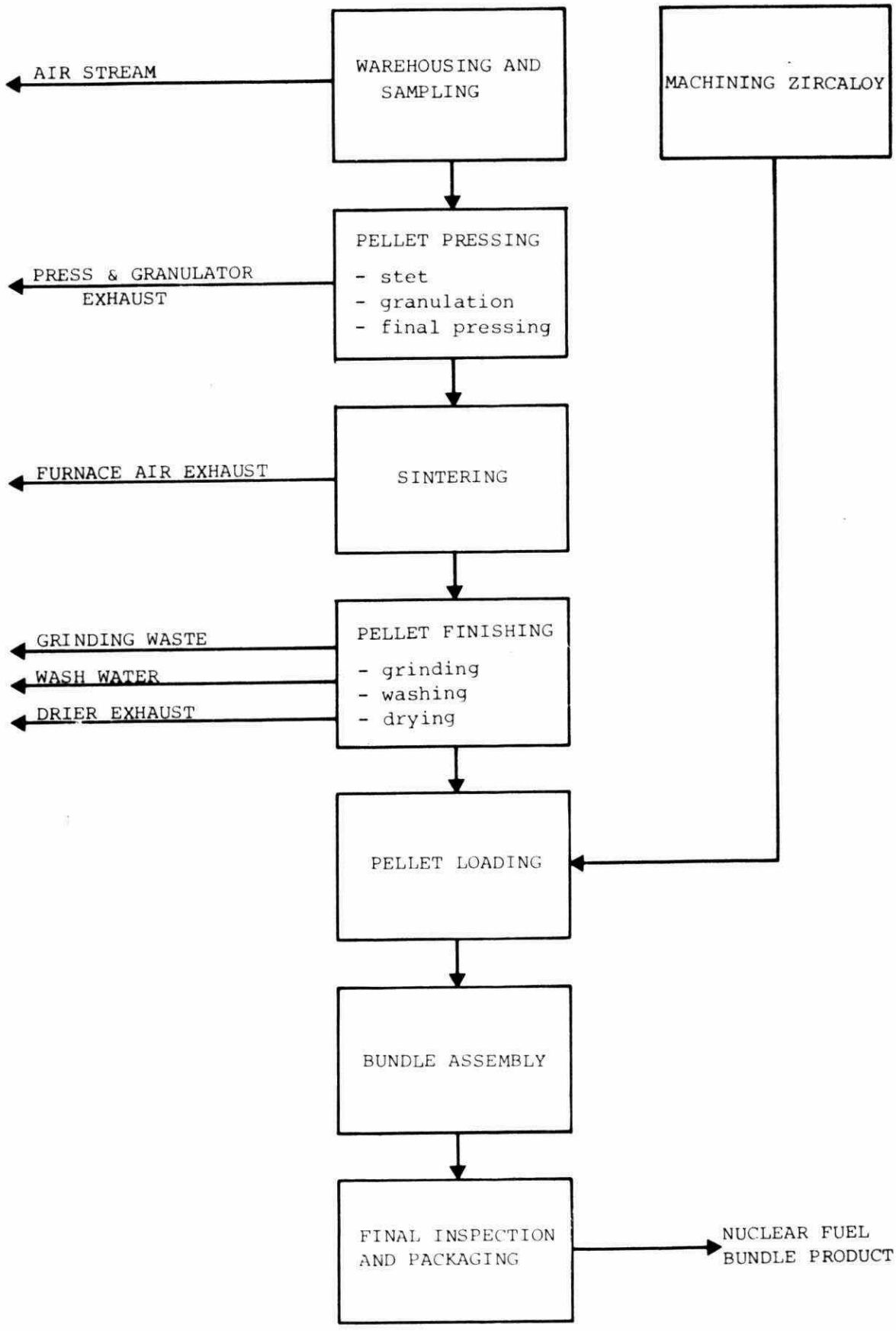
Zircaloy bar is received and inspected for defects with ultrasonics. The end caps are machined on an automatic screw machine and inspected, after which the caps are degreased, pickled, rinsed and dried.

End Supports

Zircaloy strip is inspected for compliance to specification and end supports are blanked from this strip. Inspected end supports are degreased, pickled and rinsed.

FUEL FABRICATION FACILITY - Potential Plant Emission Points

Figure 2.5



Sheaths

Zircaloy sheaths are received from the supplier, inspected and ultrasonically tested for defects. Sheaths are sorted by inside diameter size and degreased. Bearing pads and spacers are resistance tack-welded to the sheaths after which sheaths are induction brazed in a controlled vacuum environment. Sheaths are then immersed in a graphite solution, drained and air dried. Heating the sheaths in a vacuum removes all non-graphite material which is in the coating solution. Sheaths are then cut to length, the ends are reamed and deburred and the sheaths are again degreased.

(iv) Bundle Fabrication

Loading

Pellets are visually inspected for cracks or chips and are then stacked to a specific length. A pellet loading machine pushes each stack into an appropriate sheath.

Bundle Assembly

End caps are closure welded with a magnetic-force resistance welder. The final end closure is made in a controlled atmosphere of helium and argon to obtain this atmosphere inside the elements. All welds are examined carefully. Elements are machined to the correct length and profiled by a lathe to remove the weld flash and cut a profile on the face of each end cap. Elements are then degreased and a helium leak test is performed. Pickling, rinsing and drying operations follow.

Elements are assembled into bundles using a spot welder to weld each element to the end supports. A lathe is used to machine the bearing pads to a fixed diameter and the pads are deburred.

Final Inspection and Packaging

All bundles are visually and dimensionally inspected. In addition, a small percentage of bundles are monitored for surface radioactivity.

Bundles are packed and sent to the appropriate nuclear power generating station.

These operations are summarized in Figure 2.5.

References - Fuel Fabrication

1) Durant, William C. "Manufacturing CANDU fuel", Prepared by Canadian General Electric Co. Ltd. for: IAEA Study Group on Facilities and Technology Needed for Nuclear Fuel Manufacturing, Sept. 1972.

2) Page, R.D. "Canadian power reactor fuel", AECL, March 1976.

3) Page, R.D. "Canadian reactor fuel", Nuclear Power Symposium, AECL, May 1974.

4) Combustion Engineering - Superheater Ltd. Brief submitted to the Moncton City Council, "C-E Canada and nuclear fuel fabrication", July 1977.

2.2.4 CANDU Nuclear Reactor

(i) Reactor Description

Commercial, power generating nuclear stations are located in Rolphton, Bruce, and Pickering, Ontario. The nuclear reactor in a CANDU nuclear power station is simply a source of heat. (CANDU is an acronym for Canadian deuterium uranium.) A CANDU nuclear reactor uses natural uranium as a fuel. It does the same job as coal, oil, or natural gas in the more conventional thermal-electric power plants. As can be seen in Figure 2.6, in conventional thermal power stations, the heat from burning fossil fuels is used to turn water into steam to rotate turbine-generators. In nuclear power stations the heat is produced by the splitting of atoms in the uranium fuel. This latter phenomenon is called fission. The heat generated by this nuclear reaction is then transferred to the boiler via the reactor's heavy water cooling system. (see figure 2.6)

The natural uranium in the fuel consists mainly of the isotopes uranium-238 and uranium-235 (less than 1% is uranium-235). Only the uranium-235 atoms are capable of fissioning to any great extent.

The fission process is initiated by the bombardment (collision) of the uranium fuel with slow-moving neutrons. Neutrons resulting from this fission process are energetic or fast-moving. In order to sustain the fission process, these neutrons must be slowed down. This is accomplished by means of a moderator. In a CANDU reactor, this moderator is heavy water (deuterium oxide). The heavy water moderator is contained in a separate loop from that of the heavy water coolant.

Heavy water rather than light or ordinary water is used because it absorbs less neutrons and thus, is more efficient. If light water were used, the uranium would first have to be upgraded or "enriched" to a higher uranium-235 content than found in natural uranium. This is the case for reactors developed in the United States.

Fast neutrons are not the only products of fission-gamma rays and other fission products are also produced. All of these products produce heat as they are slowed down and stopped within the fuel element. The heat produced is used to generate steam to turn the turbines.

The fast neutrons produced in the fission process can penetrate the fuel cladding and are bounced around and slowed down by the heavy water until they are captured by the coolant, fuel, or other reactor components. Some of the neutron capture in the fuel sustains the fission reaction. Other captures in the fuel produce activation products such as uranium-239 (from capture by uranium-238) which decays to plutonium-239. Neutrons captured in the coolant and other materials present in the core or centre of the reactor produce other radioactive activation products.

The gamma rays produced, both as a direct result of the fission process and from the decay of the radioactive fission products, can penetrate

both the fuel cladding and the "in-core" components. It is thus necessary to shield the reactor with suitable material to stop these radiations. This protective shielding, which usually takes the form of steel or concrete or combinations of the two, safely absorbs or reflects the gamma rays at the edge of the reactor core.

(ii) Sources of Radioactivity

There is only one area in a nuclear power plant where radioactivity is produced and that is in the reactor core. The types of radioactivity produced can be classified in two categories - fission products and activation products.

The fission products remain within the fuel elements except for minute amounts, composed mainly of fission gases, which are released to the reactor coolant via occasional small defects in the fuel sheaths.

Activation products are formed by neutron bombardment of the fuel, air, coolant, moderator, and corrosion products in the coolant and moderator. Neutron bombardment of the heavy water coolant produces tritium, a radioactive isotope of hydrogen. The corrosion products arise from the minute quantities of metal, etc. that are released to the reactor coolant and moderator due to corrosion in these systems. The freed particles are then transported to and through the neutron flux in the core where some of them become radioactive.

This unwanted radioactivity can then be transferred from the core to other parts of the affected systems. In order to maintain the radiation levels in the coolant and moderator at a minimum, ion exchange resins and filters are used to remove the non-gaseous fission and activation products present. "Off-gas" systems are used to remove the radioactive gases.

(iii) Emission Pathways

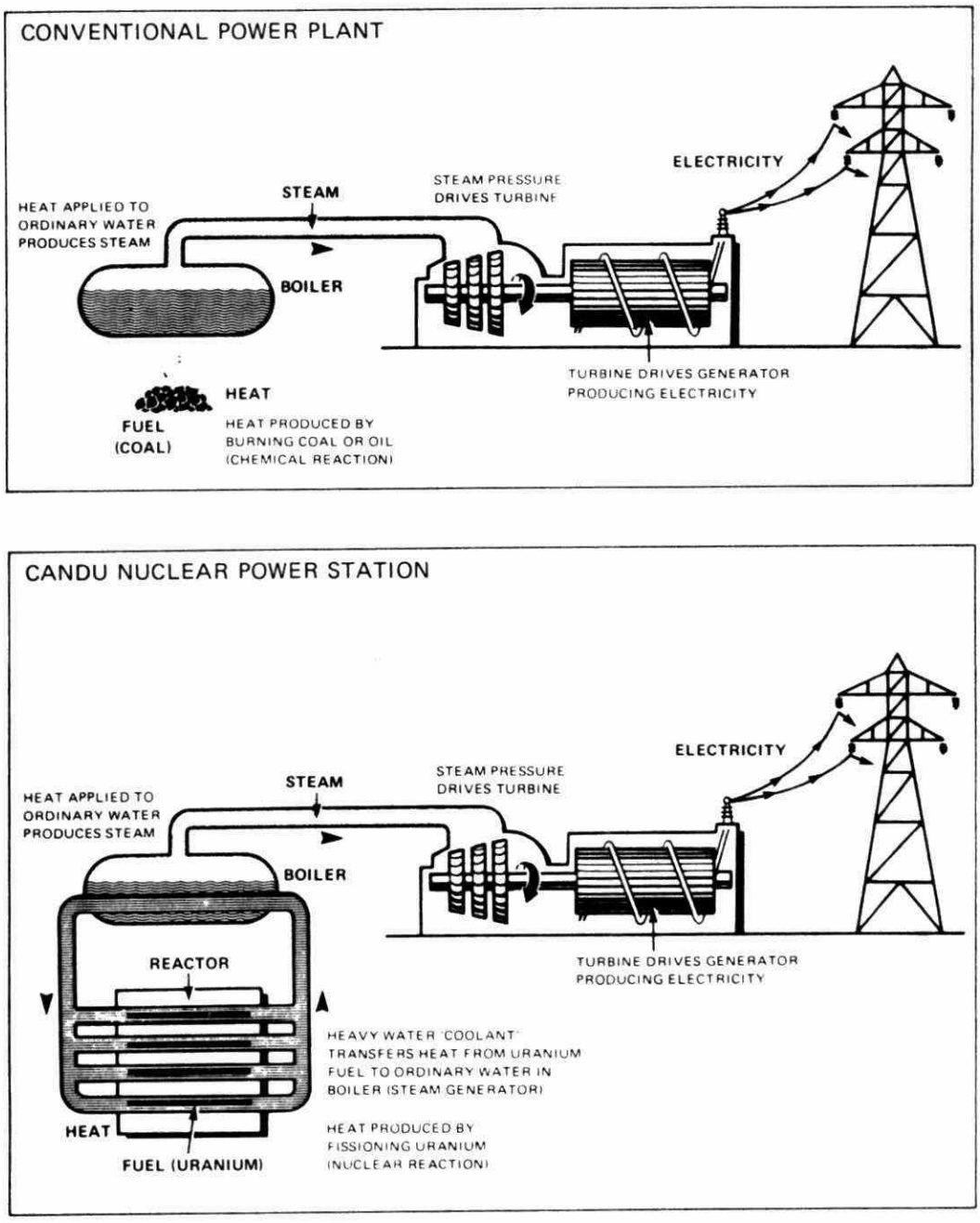
Despite careful design, construction, and operation of the reactor systems described above, small leakages do occur. These leakages release small amounts of radioactive gases and radioactive particulates to the atmosphere in the area of the leak. Radioactive liquids may also be released. Tables 2.7 and 2.8 list possible radionuclides released in air and liquid effluents from a CANDU reactor.

The gaseous exhausts are heavily filtered and monitored before being released to the environment. Normally these exhausts are all funnelled into one duct where the flow is continually sampled and monitored separately for particulates, gases such as argon-41, tritium, and iodine-131. The resulting data are displayed in the station control room so that remedial action can be taken if required.

Special drains in the controlled areas convey any liquid wastes to sump from which they are sent to storage tanks. The tanks are then sampled, the liquid analyzed for radioactive content, and either treated or

CONVENTIONAL POWER PLANT
CANDU NUCLEAR POWER STATION

Figure
2.6



Main difference between a conventional steam power plant (upper) and a nuclear plant (lower) lies in the source of heat used to make the steam that drives the turbines. In the reactor, heavy metal flows over hot uranium rods and becomes hot itself. It is then pumped through a boiler (heat exchanger) where it gives up its heat to ordinary water that is converted into steam.

TABLE 2.7

Possible Airborne Emissions - CANDU Reactor (1,3)

Radionuclide	Source	Half-life
Tritium	Activation Product	12.3 y
Noble Gases		
Ar-41	Activation Product	1.8 h
Kr-85	Fission Product	10.7 y
Kr-85m	"	4.5 h
Kr-88	"	2.8 h
Xe-133	"	5.3 d
Xe-135	"	9.2 h
Xe-138	"	14.2 m
Iodine-131	Fission Product	8.0 d
Particulates		
Co-58	Corrosion Product	71 d
Co-60	"	5.3 y
Sr-89	Fission Product	50.5 d
Sr-90	"	28.0 y
Ru-106	"	369 d
Cs-134	"	2.0 y
Cs-137	"	30.1 y

TABLE 2.8 (1,3)

Possible Liquid Effluents - CANDU Reactor

Radionuclide	Source	Half-life
Tritium	Activation Product	12.3 y
Fe-59	Corrosion Product	44.6 d
Co-58	"	71 d
Co-60	"	5.3 y
Zn-65	"	244. d
Sr-89	Fission Product	50.5 d
Sr-90	"	28.0 y
Zr-95	"	65.5 d
Ag-110m*	Corrosion Product	252. d
I-131	Fission Product	8.0 d
Cs-134	"	2.0 y
Cs-137	"	30.1 y
Ba-140	"	12.8 d
Ce-144	"	248 d
Cr-51	Corrosion Product	28 d
Mn-54	"	303 d

* Ag-110m refers to the isomeric or longer-lived state of silver - 110. The shorter-lived state has a half-life of 25's.

released to the station cooling water (for final dilution to acceptable levels) before entering the environment. It should be noted that this cooling water is not associated with the reactor as such but is used mainly to recondense the spent steam from the turbine before returning it to the boiler.

Solid waste products, such as spent fuel, ion exchange resins, filters, etc., contain the bulk of the radioactivity produced in the reactor. The spent fuel, containing more than 99% (6) of the radioactivity produced, provides its own self-contained packaging for fission products. The current practice is to store the spent fuel in a water bay area until the short-lived radioactive fission products decay.

The small quantities of solid activation products that may be plated out on the surface of the stored fuel will either remain or be slowly released into the spent fuel bay water from which they can be removed by clean-up systems. Any slightly defective fuel may continue to release small amounts of radioactivity into the water of the spent fuel bay. The soluble and particulate releases suffer the same fate as the activation products. The gaseous releases may enter the air above the bay, necessitating its control and monitoring. If the leakage is large, fuel assembly may be 'canned' to contain the activity before entering the bay. The remaining solid waste can be suitably packaged to prevent the release of activity before being removed from the controlled area for storage or disposal.

Another pathway of radioactivity release is via heavy water which has leaked out of the reactor system. This heavy water is sent to an upgrading system. Upgrading removes contaminants (including light water) from the heavy water before it is returned to the reactor system for further use. The upgrading is normally done in a batch mode, but continuous upgrading of streams bled-off from the heavy water moderator is also possible. The tritium content of the heavy water vapour lost in the upgrading system requires that this vapour be directed to a vapour recovery system before release to the atmosphere.

In addition to being transported via the air, liquid, and solid effluents, radioactivity may also be transported on clothing by personnel. For this reason separate clothing is worn inside controlled areas. Upon leaving these areas personnel remove this clothing, monitor themselves, and shower if necessary before dressing in their outside clothing.

To summarize, the radioactivity emitted from a nuclear power plant although produced in the reactor core, can be released in the following areas of the plant: (3)

a) Ventilation systems from controlled areas

b) Floor drains in controlled areas

c) Resin slurry liquids

d) Spent fuel bay

e) Heavy water upgrading system

f) Active clothing laundry

g) Decontamination centre

h) Showers and washrooms in controlled areas

i) Laboratories

(iv) Estimated Releases To The Environment

The solid radioactive waste produced (filters, ion exchange, resins, etc.) can be suitably packaged to prevent any release. This leaves the air and water flowing through the plant as the media for releases to the environment.

Airborne Emissions

As mentioned earlier, all ventilation systems in controlled or possible contaminated areas contain filters to minimize the releases to the atmosphere. For those radioactive gases and particulates that get by the filters, suitable methods of monitoring and detection are employed. To ensure appropriate dispersal, these areas are vented via the station stack.

The main airborne releases, their sources, and estimated release rates per megawatt-year of electricity (MWY(e)) generated are listed in Table 2.9.

Waterborne Effluents

Liquid releases occur via the station cooling water system. Although monitored before entering the cooling water discharge, a final check on plant liquid releases is made using a continuous sampler on this discharge in order to provide a composite sample for laboratory analysis.

Table 2.10 gives the two main categories of waterborne releases, their sources and estimates of release rates per MWY(e).

The release rates at Pickering, the only full-scale CANDU nuclear power plant which has been in operation long enough for significant measured data to be available are shown in Table 2.11. These release rates are lower than the design target of 1% of the permissible Derived Release Limit (DRL).(8) The DRL's are maximum limits for the radioactivity that may be released in accordance with the operating license issued by the Atomic Energy Control Board to each station. These limits are derived from the maximum radiation dose permitted to an individual member of the public. For the whole body dose, this is 500 mrem/y. Table 2.12 shows the estimated maximum radiation doses from Pickering for one year, 1974. (7).

TABLE 2.9

Estimated Airborne Release Rates - CANDU Reactor

Radionuclide	Source	Daily Release Rate/ MWY(e)*+
Tritium	Activation Product	0.4 Ci/d
Noble Gases		
Argon-41	Activation Product	0.1 Ci-Mev/d
Xenon,Krypton	Fission Products	
Iodine-131	Fission Product	5×10^{-9} Ci/d
Radioactive Particulates	Activation & Fission Products	4×10^{-8}

* A MWY(e) is the amount of electricity put out by a 1 MW capacity power plant, running at 100% capacity, in 1 year (365 days). The emission rates for such a plant are given on a daily, rather than a yearly, basis.

+ Derived from Ref. 3 and 5.

TABLE 2.10

Estimated Waterborne Release Rates - CANDU Reactor

Radionuclide	Source	Release Rate /MWY(e)
Tritium	Activation Product	0.025 Ci/day
Beta-Gamma		
Cs-137	Fission Product	2.0×10^{-6} Ci/d
Cs-134	"	0.8×10^{-6} "
Co-60	Activation Product	0.6×10^{-6} "
Sr-90	Fission Product	0.02×10^{-6} "
Others		0.6×10^{-6} "
	Total	4.0×10^{-6} Ci/d

* Derived from references 3,5

TABLE 2.11 - AVERAGE EMISSIONS OF RADIOACTIVITY FROM PICKERING NUCLEAR-ELECTRIC GENERATING STATION (5)

EMISSIONS TO AIR

Year	Tritium		Noble Gases		I-131		Particulates	
	Ci/d	% DRL	Gamma Ci-MeV/d	% DRL	Ci/d	% DRL	Ci/d	% DRL
1973	100	3.3×10^{-1}	110	1.8	0.015	2.5×10^{-2}	0.03	2.0×10^{-2}
1974	680	2.4×10^{-1}	120	1.9×10^{-1}	1.1×10^{-5}	1.9×10^{-2}	9.3×10^{-5}	6.5×10^{-2}
1975	560	2.0×10^{-1}	140	2.2×10^{-1}	2.6×10^{-6}	4.5×10^{-3}	2.0×10^{-5}	1.4×10^{-2}

EMISSIONS TO WATER

Year	Tritium		Gross Beta-Gamma Activity	
	Ci/d	% DRL	Ci/d	% DRL
1973	11.5	0.4	5.0×10^{-3}	0.3
1974	40.0	8.7×10^{-2}	7.2×10^{-3}	2.9×10^{-1}
1975	29.0	6.4×10^{-2}	2.6×10^{-3}	1.0×10^{-1}

(v) Generation of Spent Fuel Waste

The fuel cycle requires about 140 kg U/MWY(e)(11)*. This represents approximately seven Pickering-type bundles. This amounts to an assembled fuel weight of ~ 170 kg/MWY(e)(11). Thus, spent fuel accumulates at the rate of 170 kg/MWY(e). The coal equivalent needed is approximately 2.6×10^6 kg (4) coal yielding 1.3×10^5 kg ash.(6)

To date, spent fuel produced in Canadian power reactors is stored in water-filled, double-walled concrete tanks (spent-fuel bays). This interim storage technique serves three purposes:

1) Remove heat generated in the irradiated fuel by decay of contained short-lived radioactive fission products.

2) Provide sufficient shielding to maintain acceptable radiation levels outside the storage area.

3) Provide containment of any radioactive materials that might escape from the fuel.

Alternative interim storage concepts such as dry storage in concrete cannisters are being evaluated.

Several methods have been suggested for final disposal of irradiated fuel. These include such approaches as surface disposal, ice sheet disposal, disposal in outer space, disposal on or in ocean plains, and geological containment (in salt-formations, crystalline rocks, shale, and volcanic rock). An acceptable national plan for the management and disposal of nuclear wastes is clearly needed to prevent a delay in the country's nuclear power program. The recently completed report on "The Management of Canada's Nuclear Wastes" emphasizes the need for developing such a management technique.(12)

* uranium required varies depending on source (Ref. 2, 3, 4, 6, 7, 8, 9, 10, 11).

References - CANDU Reactor

1. Burrill, K.A. "How Unwanted Radioactivity Moves Around," AECL-4429, 1973

2. Hatcher, S.R. "CANDU Fuel Cycle Alternatives - What are They and Why are We Interested", CNA Seminar on CANDU Fuel Cycle Alternatives. May, 1976.

3. Maclaren Atlantic Limited and Delworth, Secord, Meagler and Associates Limited", Pt. Lepreau Environmental Impact Assessment", Moncton, 1977.

4. Delaney, B. "The Energy Bridge - Canada and the World", April, 1977.

5. Ontario Hydro, "Emission Tables 1974, 1975" (see Table 2.11).

6. Dyne, P.J. "Managing Nuclear Wastes", AECL-5136, May, 1975.

7. Canadian Nuclear Association, "Nuclear power in Canada, questions and answers", Toronto: Canadian Nuclear Association, 1975.

8. Canadian Nuclear Association, "The role of nuclear power in Ontario - submission to the Royal Commission on electric power planning", Toronto: Canadian Nuclear Association, 1976.

9. Fanjoy, G.R. and Bain, A.S. "Pickering Fuel and Fuel Cycle" Nuclear Engineering International, June 1970, page 515.

10. Atomic Energy Control Board, "Into the Age of Nuclear Power", AECL-386, Atoms for Development, Geneva 1971.

11. Durant, W.C., "Manufacturing CANDU Fuel", prepared by Canadian General Electric Co. Ltd. for: IAEA Study Group on Facilities and Technology Needed for Nuclear Fuel Manufacturing Sept. 1972.

12. Aikin, A.M., J.M. Harrison and F.K. Hare, "The Management of Canada's Nuclear Wastes", Energy Mines and Resources Report EP77-6, 31 August, 1977.

2.3 Institutional Sources

2.3.1 Medical

Radiation exposure to the general population due to medical and dental practices represents a significant percentage of the total exposure to radiation, and is the largest manmade contributor. Figure 2.7 illustrates this point in terms of genetically significant dose rates, in which the medical and dental sources represent about 30% of the total genetically significant dose, and 90% of the total man-made radiation dose. The following section, although not directly relevant to environmental aspects except with regard to waste disposal, is considered to provide relevant data on the role of medically related exposures as an important component of man's overall background radiation exposure.

Medical and dental applications of radioisotopes include such items as:

1) Diagnostic Radiography
2) Radiation Therapy
3) Nuclear Medicine
4) Laboratory Techniques

As well as patients receiving radiation exposure, medical/ dental staff and visitors, to an extent, also receive exposure from the same sources and, in some cases, from the patients themselves.

(i) Diagnostic Radiography

The majority of medical radiation exposure to the population can be attributed to diagnostic radiography. X-ray, fluoroscope and cinescope diagnostic examinations in 229 hospitals in Ontario totalled 4,814,348 in 1974 (excluding dental x-rays). A breakdown of the types and frequency of the examinations is shown in Table 2.13.

TABLE 2.13

Radiology Examinations in Ontario (1)

Examination	Percentage of Total Examinations
Chest Examinations	23.3%
Fluoroscope	9.5%
TB X-rays	4.3%
Cinescope	0.6%
Other X-rays	60.7%
Serviced by diagnostic radiologists	1.6%

Radiology contributes an annual genetically significant dose of about 55 mrems to the individual. Abdominal examinations represent 90% of this dose (2).

The estimated mean gonadal dose in the United States for 1970 from abdominal examinations other than flat plate examinations was reported as 857 mrad per examination for males and 524 mrad per examination for females. Barium enemas resulted in a mean gonadal dose of 903 mrad per examination for females and 470 mrad per examination for males. Similarily, mean gonadal doses to females from lumbar spine examinations and intravenous or retrograde pyelograms were estimated as 721 and 588 mrads per examination and to males, 507 and 437 mrads per examination, respectively (3).

(ii) Radiation Therapy

The use of radioisotopes in the treatment of cancer patients is perhaps the best-known therapeutic application of radiation, contributing an average estimated 5 mrem per individual annually to the genetically significant dose (2). As well, patients with tuberculosis, Hodgkins's disease, hyperthyroidism, etc. may be treated with radiation by a variety of methods. There are a total of 26 cobalt-60 and 2 cesium-137 therapy units in operation in Ontario.

Radiation therapy constitutes a minor portion of the total medical exposure of radiation to the general population as illustrated in Figure 2.7.

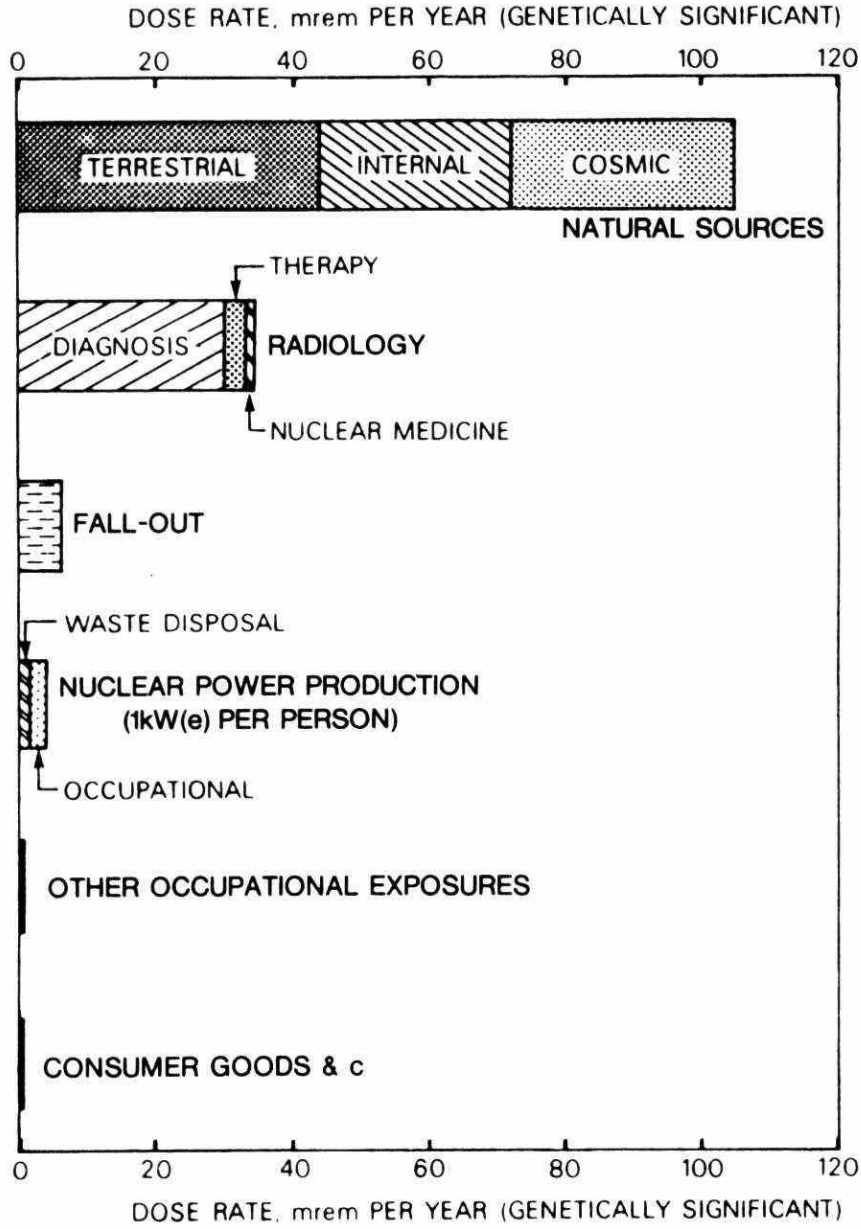
(iii) Nuclear Medicine

Radioactive pharmaceuticals are administered directly into the body and serve to study pathways and stages of metabolism (e.g. labelling protein for metabolism studies).

The radiation exposure to the public from nuclear medicine is relatively small as shown in Figure 2.7 and Table 2.14.

RADIATION DOSES FROM NATURAL AND MANMADE SOURCES

Figure 2.7



Annual genetically significant dose rate, as averaged through whole population.

TABLE 2.14

Radiation Dose from Exposure to Medical Practice (4)

Millirem per annum per person

	bone marrow (U.K. data)	germ cells (U.K. data)	germ cells (other data)
Diagnostic radiology	32	14	10-50
Radiotherapy	12	5	2-5
Nuclear medicine	2	0.2	< 1
Total (approx.)	46	19	12-56

Since nuclear medicine and radiopharmaceutical therapy often involve the use of unsealed radioactive sources, there is a potential hazard to the medical staff in handling these sources. For example, skin doses to staff handling radioactive syringes range from 1 to 70 mrad/min per 100 μCi as shown below.

Skin doses to fingers in contact with syringes (maximum estimates) when unshielded syringes are used (5).

Nuclide	Dose (mrad/min per 100 μCi)
Technetium-99m	1-5
Indium-113m	≅ 15
Iodine-131	14-70
Gold-198	8-20

Other potential sources of exposure to medical staff and patients would be ingestion or inhalation of radionuclides or external exposure from patients receiving radionuclides for treatment or diagnostic studies. The excreta and body fluids of patients receiving radiopharmaceutical therapy may contain radioactivity as well and present another source of exposure to the medical staff.

(iv) Laboratory Techniques

Electron microscopy, fluorescence spectrometry and gas chromatography are a few of the analytical techniques which require the use of radionuclides.

The electron microscope uses uranyl acetate as a positive or negative stain and for shadowing purposes. The fluorescence spectrometer uses radioactive sources to determine calcium content for bone mineralization studies, to measure potassium and iodine levels in blood, copper, sodium and phosphate levels in plasma, and sulphur in protein fractions. The gas chromatograph uses plated sources in the detection section of the unit. A plated source consists of a metal backing upon which the radionuclide is deposited. For a given source activity, a plated source is a greater potential exposure hazard than a sealed source, but a lesser hazard than an unsealed source.

Some radionuclides and their respective source activities commonly used for plated sources in gas chromatography are: 100-300 mCi tritium, 10-20 mCi strontium-90, 2-15 mCi nickel-63, 0.05-0.1 mCi radium-226, 0.1 mCi lead-210, cobalt-57 and oxygen-14 (for standardization). External radiation from detectors containing strontium-90 or radium-226 is usually attenuated by shielding material built into the chromatograph detector unit. At 3 cm from the sides of this unit exposure rates are around 10 mR/h, but at the open anode end, the dose rate may increase to 1000 mR/h (5).

Activity can escape as a result of (i) excessive heat, (ii) chemical attack by a cleaning solvent or a material being analyzed, (iii) radioactive gas emission and, (iv) mechanical damage to the source.

Air ionizers which remove static charge from precision balances, microtomes and photographic plates also use microcurie levels of plated sources.

There is a hazard to external exposure in labs where stock solutions are held or where dispensing and labelling of radioactive materials are performed. Contamination of working surfaces, equipment or the worker himself is possible in the case of leakage of sealed or plated sources, or accidents in labs and dispenseries.

Principal research studies during 1966 in the United States included labelling hormones with iodine-131 in metabolic studies (16% of total administrations), labelling aldosterone with tritium and carbon-14 in metabolic studies, (5.6% of the total), and labelling albumin with iodine-131 for blood volume determination, (4.6% of the total). Other studies included adrenal secretion, blood flow, lung and heart scanning, cardiac output, autoradiography, iron absorption, plasma clearance and radioimmunoassay. Radionuclides such as xenon-133, krypton-85, iron-59, calcium-47, indium-113m, technetium-99m as well as iodine-131, tritium and carbon-14 were used in these studies (6).

References - Medical

1. Statistics Canada, "Hospital Statistics, Volume 1 - Beds, Services and Personnel." 83-227 (1974).

2. U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation." Washington, D.C. National Academy of Sciences, 1972.

3. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological Quality of the Environment." EPA-520/1-76-010. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1976.

4. Newcombe, Howard B., "Public Health Aspects of Radiation." Chalk River, Ontario: Atomic Energy of Canada Ltd., 1976.

5. International Commission on Radiological Protection. "The handling, storage use and disposal of unsealed radionuclides in hospitals and medical research establishments." ICRP publication 25. Annals of the ICRP, Vol. 1, No. 2. Oxford: Pergamon Press, 1977.

6. Stanford Research Institute, "Survey of the use of radionuclides in medicine." Rockville, Maryland: U.S. Dept of Health, Education and Welfare, Bureau of Radiological Health, 1970.

7. Aikin, A.M., Harrison, J.M. and Hare, F.K., "The management of Canada's nuclear wastes". Energy, Mines and Resources Canada, Report EP 77-6. Ottawa: Supply and Services, 1977.

2.3.2 Universities

Universities use radioactive sources extensively in many areas of research. The University of Toronto is the largest user of radioisotopes among the universities in Ontario, handling an estimated 40% of the total radioactive sources accounted for by all Ontario universities. McMaster University handles another 20% of this total radioactivity, and the remaining 40% is attributed to all the other universities in Ontario (e.g. Western, Windsor, Waterloo, Guelph, Queen's, etc.).

Universities produce some of their own radioisotopes using accelerators and nuclear reactors. Presently, there are two slow poke reactors in use in Ontario, one in Ottawa operated by AECL, and the other at the University of Toronto. In addition, McMaster University operates a larger 5 MW nuclear reactor. Approximately 6 accelerators are presently in use in Ontario.

The University of Toronto obtains 90% of their radioactive material from outside suppliers. Three to four shipments of 10 mCi to 1 Ci sources of activity are received daily. These suppliers include Amersham, New England Nuclear, Charles E. Frosst, Limited, and ICN. All shipments are sent via Montreal airport. A special terminal in the airport is used to distribute shipments of radioisotopes to trucks and other aircraft, which in turn carry shipments to other Canadian locations.

The most commonly used radionuclides are listed in Table 2.15, along with the total activity per annum used by the University of Toronto. These represent about 80% of all the radioisotopes in use at the University of Toronto.

Table 2.15

Common Radionuclides in Use at the University of Toronto

Radionuclide	Total Activity/y in [Ci/y]
Tritium (most common)	200-300
Carbon-14	10-20
Sulphur-35	≅10
Phosphorus-32	≅10
Iodine-125	≅10
Iodine-131	≅10

Sealed sources are used in gas chromatography, fluorescence spectrometry, other laboratory procedures, nuclear medicine research and radiation therapy. The University of Toronto has one sealed source of 10,000 Ci of cobalt-60 in their medical building for therapy procedures.

Similarly, McMaster University uses sealed sources of 5,000 Ci cobalt-60 and 2,000 Ci cesium-137 for radiation therapy. In addition, there are 31, cobalt-60 source "gamma cells" in operation in Ontario. These units are used in research to investigate the effects of radiation.

Medical research accounts for about 75% of the radioisotopes used by universities. The remaining percentage is divided up between all of the other facilities for use in research (e.g. engineering, applied sciences, health and life sciences, arts and sciences, agriculture, forestry, etc.), with a small percentage used for teaching purposes.

The University of Toronto has 380 labs which use radioactive material with 800 people in total handling radioactive sources, while McMaster University has about 500 people handling radioisotopes.

Storage systems vary with each institution. McMaster University has a central collection system from which radioactive material is distributed to each user, between 2-4 p.m. on the day of arrival. The University of Toronto does not have a central collection system but instead, each department holds the material in their general storerooms. Shipments are checked for external contamination and the storerooms retain shipments until transfer to the user.

The Health Physics or Radiation Protection officer associated with each university is normally the holder of the consolidated license from the AECB. It is mandatory that this officer keep records of all shipments received and of all wastes disposed. In addition, both McMaster University and the University of Toronto have internal licensing systems which record the amounts of radioactivity each user is allowed and cumulative amounts used.

References - Universities

1. International Atomic Energy Agency. "Radioisotope X-Ray Fluorescence Spectrometry". Technical Report Series No. 115. Vienna: IAEA, 1970.

2. International Commission on Radiological Protection. "The Handling, Storage, Use and Disposal of Unsealed Radionuclides in Hospitals and Medical Research Establishments". ICRP publication 25. Annals of the ICRP, Vol. 1, No 2, Oxford: Pergamon Press, 1977.

3. Personal Communication with Dr. John Harvey, Radiation Protection Officer, McMaster University, March, 1978.

4. Personal Communication with J. Jardine, AECB, March, 1978.

5. Personal Communication with W.H. Ridge, Radiation Protection Officer, University of Toronto, February, 1978.

6. Personal Communication with K. Badham, AECL, March 1978.

2.3.3 Waste Disposal

Radioactive wastes from medical and educational institutions are dealt with in two ways. First, by allowing radioactive wastes to be stored under controlled conditions until they have decayed to levels considered non-radioactive, and then treating them as conventional solid or liquid waste. Second, by disposing specific quantities of activity into the environment so that combined radiation doses are within statutory limits.

Liquid radioactive wastes encompass solutions and suspensions of radioactive substances such as solvents from scintillation counting, blood and excreta from patients receiving radiopharmaceuticals, and spills and washwater from cleaning contaminated articles. An estimated 95% of the liquid waste collected by these institutions are solvents from scintillation counting. The majority of liquid wastes have low levels of activity.

Solid radioactive wastes consist of used molybdenum and technetium generators, contaminated syringes, glassware, protective clothing, linen, cleaning materials, bench covers, insoluble radioactive material and contaminated animal carcasses. Gaseous radioactive wastes are primarily a byproduct of incineration of radioactive materials.

Disposal practices for these three forms of waste are considered below.

(i) Liquid Wastes

Waste disposal practices vary from institution to institution. For example, washwater from cleaning contaminated articles and laboratory urine samples are commonly disposed of through the conventional sewage system, however, McMaster University also disposes of low level carbon-14 and tritium liquid waste, spills and decayed liquid waste through the sewage system. The University of Toronto, which has a policy that no radioactive waste will go into standard garbage systems, if it can be avoided, collects these same wastes for disposal as radioactive waste.

Presently, the University of Toronto is responsible for the collection of waste from 22 institutions in addition to its own. The University of Toronto disposes of 2500-3000 gallons of waste per year. Approximately 50% is from the university, 25% is collected from the Princess Margaret Hospital and the remaining 25% is collected from the other 21 institutions including Toronto General Hospital, Hospital for Sick Children, York University, Seneca College, and the Ministry of Natural Resources.

The collected wastes are shipped in glass vials, in trays of 1000 vials to Chalk River Ontario. Seventy-five to a hundred trays are shipped for disposal per month. The activity of this waste is limited to one-tenth of the scheduled quantity per litre. Notice is sent prior to shipment and acknowledged by AECL in Chalk River upon receiving the shipment of waste.

The University of Toronto supplies the 22 other institutions with 5 litre containers, filled with an absorbent material called "Sealite". Liquid wastes are essentially solidified when poured into these containers. Liquid wastes disposed of in this manner include solvents from scintillation counting, blood and urine from patients receiving radio pharmaceuticals, unused stock solutions, and long-lived radionuclides used in medical research. Spills of radioactive material are cleaned up with absorbent paper or sawdust and the cleaning materials are disposed of as a solid radioactive waste. Some spillage can make its way to the sewage system. Thus, the University of Toronto monitors effluent from some of their facilities on a regular basis.

McMaster University separates liquid waste into two categories, combustible and non-combustible waste. Solvents containing radionuclides (e.g. from scintillation counting) can be incinerated for the most part, except when iodine-125 is present. In that case, the waste is allowed to decay for 6-8 months before incineration. Non-combustible liquid waste is collected in 5 gallon polyethylene containers which are packed in 45 gallon drums and held in the solvent storage room until the University's truck collects the drums and transports them to Tricil (a licensed disposal facility).

As a rule, high level liquid wastes are stored behind shielded areas in radioactive waste storage rooms. Waste is allowed to decay until it is considered non-radioactive and is disposed of by incineration or released to standard sewage systems. Since high level waste is not customarily encountered from medical and educational institutions, special instructions and containers are obtained from AECL when a high level waste is generated (e.g. removing a radium-226 source in a special container and relocation to Chalk River for ultimate disposal).

(ii) Solid Wastes

Solid waste is temporarily collected in large plastic trash cans which are usually located in a room out of the way of major traffic. The frequency of emptying these waste containers ranges from daily to twice per week.

As with liquid waste, the disposal practices dealing with solid waste vary between institutions. McMaster University divides solid waste into combustible and non-combustible waste. Combustible wastes, the majority of which are contaminated animal carcasses, are burned in the University's incinerator. Non-combustible waste is bagged in polyethylene bags, and packed in 45 gallon drums for shipment to Chalk River via a University truck. Any combustible wastes considered too high a level to incinerate, such as spent ion exchange resins, are also shipped to Chalk River.

The University of Toronto has a compactor to consolidate solid wastes before they are packed into 45 gallon drums and shipped to Chalk River. Some animal carcasses are incinerated at the University, in which case, the residual ash is sent by University truck to Chalk River for disposal. Any animal carcasses not incinerated are disposed of as solid radioactive waste.

The University of Toronto also collects wastes from 22 other institutions. The Princess Margaret Hospital stores waste in an area near their high level lab until collected by the University. The waste storage room is equipped with a shielded area to allow for decay of higher level waste. All solid waste is double bagged, syringes, pipettes and needles are capped and bagged, and contaminated animal carcasses are frozen and bagged. The University also disposes of used molybdenum and technetium generators from medical institutions.

(iii) Airborne Releases

Waste incineration results in releases of radioactive material to the air (e.g. tritium as water vapour or carbon-14 in carbon dioxide), and/or retention of radioactive material in the ash. The University of Toronto estimates air emissions by mass balance calculations that include ash retention data of each radionuclide. All residual ash is disposed of as a solid radioactive waste.

McMaster University monitors residual ash and fly ash collected by a precipitator. The ash is disposed of as a conventional waste since the level of radioactivity is low.

Most institutions have a Radiation Protection Officer or equivalent, who is held accountable for proper waste disposal. The officer is responsible for keeping accurate records of disposals and decay including dates, quantities, methods of disposal and sources.

Special janitorial services or trained laboratory technicians are responsible for cleaning and monitoring potentially contaminated areas, collecting all radioactive waste and transferring waste to temporary storage areas.

References - Waste Disposal

1. Brodsky, A. "Principles and practices for keeping occupational radiation exposures at medical institutions as low as reasonably achievable. Draft", NUREG-0267. Washington, D.C.: U.S. Nuclear Regulatory Commission, 1977.

2. Canada, Department of National Health and Welfare, Radiation Protection Division. "Course manual, radiation hazard control in hospitals", RPD-TM-1. Ottawa: Department of National Health and Welfare, 1968.

3. International Commission on Radiological Protection. "The handling, storage, use and disposal of unsealed radionuclides in hospitals and medical research establishments". ICRP publication 25. Annals of the ICRP, Vol. 1 No. 2. Oxford: Pergamon Press, 1977.

4. Personal Communication with Dr. J. Harvey, Radiation Protection Officer, McMaster University, March, 1978.

5. Personal Communication with Dr. Leung, Radiation Protection Officer, Princess Margaret Hospital, March 1978.

6. Personal Communication with W.H. Ridge, Radiation Protection Officer, University of Toronto, February 1978.

7. Stanford Research Institute. "Survey of the use of radionuclides in medicine". Rockville, Maryland: U.S. Dept. of Health, Education and Welfare, Bureau of Radiological Health, 1970.

8. Thompson, Carolyn H., et al. "Control of radioactive materials on the medical science campus". Health Physics 32 (March 1977): 179-184.

9. Tolan, John H. "Radioactive waste disposal in the university environment, summary of data, collected in 1971". Columbia, Missouri: University of Missouri, Radiation Safety Office, 1973.

2.4 Industrial and Commercial

The industrial and commercial applications of radioisotopes are numerous and highly diversified. This section will serve to introduce the most important of these applications.

Radionuclides are utilized in a wide variety of industries, in such processes as sterilization, polymerization, irradiation catalysis, vulcanization and chemical grafting. Gauging, radiography and radioactive tracing are commonly used in measurement and control engineering, and industrial research.

Commercial uses of radionuclides include radioactive sources in luminous-dial watches and ionizing smoke detectors.

Radioactive sources are applied either in encapsulated form, or, are injected directly into a process or process fluid. Leakage, accidents and improper waste disposal are potential pathways by which radioactivity from a sealed source could enter the environment. Radioisotopes injected into a process or process fluid may also enter the environment through process losses or disposal practices.

During the course of this study, many industrial and commercial applications of radioisotopes were identified; however, specific data pertaining to amounts of radioactivity and in some cases even the actual radionuclide utilized were not available. Information on exposures to the individual due to such radioactive sources is also limited.

Table 2.16 is a partial list of radioisotope applications, specific sources and areas of use. Gaps in the table indicate lack of available information. The major gap is in the area of waste disposal, that is, the ultimate fate of these radioisotopes.

Information specifically pertaining to present day applications of radioisotopes in Ontario has not been documented. However, such procedures as industrial radiography and industrial tracing are common practice in North America and the use of radionuclides in process control instrumentation is a general industrial application. There are 716 instrument gauges using radioactive sources in present use in Ontario.

Three cobalt-60 source, production irradiators are being used in Ontario primarily for sterilizing medical supplies. These are located in Toronto, Peterborough and London.

Products such as luminous-dial watches and clocks, nuclear-powered pacemakers, colour T.V. sets and ionizing smoke detectors are commonly used by Ontario consumers. There are an estimated 500,000 ionizing smoke detectors in use in Ontario.

The available information on dose estimates for various industrial and commercial applications is summarized in Table 2.17.

References - Industrial and Commercial

1. Atomic Energy of Canada Limited. "Nuclear Power: the Canadian issues - a submission from Atomic Energy of Canada Limited to the Royal Commission on Electric Power Planning in response to the commission's issue paper no. 1" Nuclear Power in Ontario". AECL-5800. Chalk River, Ontario: AECL, 1977.

2. Bowen, H.J.M. "Chemical applications of radioisotopes". London: Methuen and Co. Ltd., 1969.

3. Cameron, J.F. and Clayton C.G. "Radioisotope instruments part 1." International Series of Monographs in Nuclear Energy Vol. 107. Toronto: Pergamon Press, 1971.

4. Darley, J.J., and Ezol, H. "Potential hazards of uranium and its compounds in electron microscopy: a brief review." Journal of Microscopy 106 (1976): 85.86.

5. "Development of depleted - uranium catalysts for destruction of air pollutants in automobile exhaust." PB 171 980. Washington, D.C. Bureau of Mines, 1961.

6. International Atomic Energy Agency. "Commercial portable gauges for radiometric determination of the density and moisture content of building materials: a comparative study." Technical Report Series no. 130. Vienna, IAEA, 1971.

7. International Atomic Energy Agency. "Neutron moisture gauges". Technical Report Series no. 112. Vienna, IAEA, 1970.

8. International Atomic Energy Agency. "Radioisotope X-ray fluorescence spectrometry." Technical Report Series no. 115. Vienna, IAEA, 1970.

9. Johnson, J.E. "Smoke detectors containing radioactive materials." Cedar Knolls, N.J.: Pyrotronics, n.d.

10. "Kirk-Othmer Encyclopedia of Chemical Technology", 2nd ed. S.V. "Radioisotopes".

11. "Kirk-Othmer Encyclopedia of Chemical Technology", 2nd ed. S.V. "Thorium and thorium compounds".

12. Kosmoki, Alfred "Radionuclides in scientific and technical fields." Wasser Luft und Betrick 13 (December 1969): 469-471.

13. McElheny, Victor K. "Technology: Sewage disinfected by electron-beam bombardment." New York Times, 3 November, 1976.

14. Newcombe, Howard B. "Public health aspects of radiation." Chalk River, Ontario: Atomic Energy of Canada Ltd., 1976.

(Continued after Table 2.17)

TABLE 2.16: INDUSTRIAL AND COMMERCIAL APPLICATIONS OF RADIOISOTOPES
(1 to 24 inclusive)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY			
1. Air Ionization			- to ionize air and eliminate static charge buildup
- Smoke Detectors	Ra-226 now replaced by Americium-241 (Am-241) and some Nickel-63 (Ni-63) Industrial sources: 80 µCi Am-241 maximum 15 µCi Am-241 average Commercial sources: 1 µCi Am-241 average or 0.1 µCi Ra-226 average	Industrial and Commercial Smoke Detectors	- approximately 500,000 ionization smoke detectors in Ontario - exposure from commercial detectors; 10 inches away, 8 h/d, 1 year: 0.5 mrem/y shielded 36.8 mrem/y unshielded
- Lightning Rods	1 mCi Ra-226 on the tip	Industrial and Commercial	- 50,000 in the world
- Spark-Gap Irradiators	limit: 1 µCi Co-60/ea	Spark-ignited Fuel-oil Burners	
- Paper Rolling Static Electricity Bars	α source	Pulp and Paper	- static electricity is removed as paper is rolled

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
2. Luminosity			- the energy of the radio-isotopes comes out as a light-emitting device
- Luminous Paint	Tritium (H-3)	Paint Industry	- airlines equip planes with H-3 activated signs
- Signal Lamps			
- Instrument Calibration	Up to 600 mCi krypton-85(Kr-85)		
- Watch and Clock Dials	Ra-226 is now replaced by H-3 and promethium-147 (Pm-147) Average Activity: 5 mCi H-3 0.5 µCi Ra-226	Commercial Product	- a liquid crystal display watch containing a maximum of 200 mCi tritium contributes an estimated dose of 0.6 mrem/y - a radium-226 dial watch contributes an estimated 3 mrem/y
- Incandescent Gas Mantles	Thorium nitrate		
3. Electric Power Source			
- Thermoelectric Generator	Strontium-90 (Sr-90)	Industrial	- 6.5 to 60 W generators

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Nuclear-Powered Pacemaker	2.5 Ci Plutonium-238 (Pu-238)	Consumer product	- by 1975, 50 pacemakers were licenced in Canada - Exposure: <5 rem/y to owners 7.5 mrem/y to family 0.2 mrem/y to non-family
4. Radiography			
- X-raying Welds Castings and Machine Parts	X-rays	Industrial Inspection of Machinery and Finished Products	- inspection of mechanical parts, welds and castings for flaws - inspection of internals e.g. bubble trays - ammunition inspection
- Deposit Formation Inspection	4 Ci and up	Industry	
- Examination of Hollow articles		Civil Engineering	- examining cement columns, etc.
- Detection of Explosives			
5. Instrumentation			
- Level Gauge	Detergent Monitoring Source: Polonium-210/Beryllium (Po-210/Be)	Package Monitoring in Food and Beverage, Pharmaceutical and Detergent Manufacturing	- to measure levels of products in containers e.g. soup, toothpaste, pills or detergent

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Level Gauge (cont'd)	20 mCi Co-60 used in Pulp and Paper and Petroleum and Coal level gauging	Level Measurement in Process Equipment in Petroleum and Coal, Medical and Pharmaceutical, Textile, Pulp and Paper, Glass, Basic Metal and Chemical Industries, Aircraft and Storage and Transport Vessels	- measures levels of coke in drums, chemicals in mix tanks, oil in aircraft tanks, grain in silos, rubber products in transport and process vessels, sand/cement in hoppers and furnaces, viscose fabrics in dissolvers, woodchips and pulp digests in preheated and bleaching towers, molten glass or metal in furnaces, dust in electrostatic precipitators, etc.
	Welded radioactive material: 10 µCi Co-60 Bullets shot into casing 3 mCi/each	Mining and Quarrying	- depth markers in a borehole casing for borehole logging
	Thallium-204(Tl-204)	Fur Industry	- count number of pelts in a pile
	0.3 µCi silver-110 (Ag-110) per check-ball	Ammunition Manufacture	- small amounts of radioisotope in each gas check-ball in order to check locations of critical parts

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Density Meter	β-gauges used in Food and Beverage, Tobacco- 10 mCi Sr-90, Textiles- Thalium-170(Tm-170) γ-gauges used in Rubber Industry Other known sources: 10 mCi Ra-226/Be 100 mCi Am-241/Be 3 mCi Ra-226 10 mCi Cesium-137 (Cs-137) 10^5 n/s Pu-238/Be Co-60	Process Measurement and Control in Mining and Quarrying, Food and Beverage, Tobacco, Textile, Pulp and Paper, Rubber, Chemical, Petroleum and Coal, Sewage, Non-Metallic Mineral, Basic Metal and Ammunition Processes	- controlling densities of process materials such as: ice cream, tobacco in cigarettes, polymer and synthetic yarn before spinning, pulp, lacquer, clay, lime, sand, cement, latex, hot brine, organics, acids and alkalis, catalysts, sewage sludge, explosives and mineral powders - used to determine mass flow rates for pouring sugar into bags, transport of coal, ores and sand, flow of oil, for flotation, leaching and gravity concentration processing

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Density Meters (cont'd)	C-14 in soyabean density Pm-147 in cotton density Cs-137 in silage density 2 mCi Cs-137 in cabbage density in fields C-14 or 1 mCi Sr-90 or 10 mCi Co-60, Cs-137, Iridium-192(Ir-192) in wood density measurement	Product Measurement in Agricultural, Forestry and Fishing, Food and Beverage, Textile, Detergent and Building Material Industries	- measurement of density of soyabean, cotton, silage, wood, processed foods, fabrics, detergent, building materials, and cabbage density in fields
	C-137 used in soil permeability tests Tm-170 used in testing dyes	Research Application in Agricultural, Forestry, Textiles, Petroleum and Coal, Electricity and Water, Meteorology, Geophysics, and Hydrology	- measuring soil permeability distinguishing between potatoes and earth on a conveyor belt, testing garments for wear, researching fluidized catalytic processes measuring heat transfer efficiencies, onset of steam formation, measuring upper atmosphere density, atmospheric gas composition and silt content in rivers, investigating dye characteristics
		Civil Engineering and Construction	- structure stability, concrete vibrator efficiencies, location of reinforcing bars

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Density Meters (cont'd)	1 Ci Co-60	Petroleum and Coal Interface Detection	- different grades of oil are pumped consecutively through one line and the interfaces between two grades are detected for easy separation
	Tm-170 Sr-90	Borehole logging	- measure fluid density in the borehole, locates interfaces and changes in fluid characteristics, locates position of ingress of gas or water into borehole
- Thickness Gauges	Leather mass/unit area: Cerium-144/ Praseodymium-144 (Ce-144/Pr-144) Thread thickness: 100 mCi Kr-85	Measuring mass per unit area or length in Textile, Pulp and Paper, Leather, Rubber, Non-Metallic Mineral Industries	- measures mass per unit length of thread mass per unit area of paper and paperboard, leather, rubber sheets, foam rubber, coated rubber, glass sheet, abrasive paper and asbestos fibres
	Metal coating thickness on Bi-metallic casts for printing plates: 100 mCi Tl-204 Thickness of hot- and cold-rolled steel metal tubes: 25 Ci Co-60	Measuring thickness of coatings and sheet material in Mining and Quarrying, Food and Beverage, Textile, Wood and Cork, Pulp and Paper, Printing and Publishing, Chemical, Petroleum and Coal, Medical and Pharmaceutical, Steel and Metal Product Industries, Aircraft, Photographic Equipment, and Jewellery	- measuring thickness of layers of coal on the floor, biscuits as one flat sheet, sheet material such as plywood, chipboard and veneers, coatings of adhesives, polyethylene films, metal coatings on printing plates, roofing paper and shingles, wall thickness of pipes and vessels, applied coatings on pills, hot- and

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Thickness Gauges (cont'd)			cold-rolled steel metal tubes and rods, coated nuts and bolts, ice detectors on aircraft, coating or photographic papers, precious metal coating, snow and soot deposition
		Research in Agriculture, Forestry, Textiles, Pulp and Paper, Rubber, Basic Metals	- measuring mass per unit area of leaves for water economy and balance in plants studies, moisture pickup and drying and wear and tear of fabrics, wear of tires and furnace walls - studies of paper formation
- Moisture Gauges	Pencil Manufacturing: Sr-90 Other known sources: 100 mCi Pb-210/Be 0.1 µCi Ra-226 - Am-241/Be - Po-210/Be - Pu-238/Be - Ra-226/Be 0.0044 µCi Am-241	Moisture content measuring in Agriculture, Forestry, Food and Beverage, Pulp and Paper, Chemical, Petroleum and Coal, and Construction Industries	- measuring moisture content of soil, vegetation for irrigation, soil management, water balance studies - measuring moisture content of lactose, wood chips, pulp, detergents, bulk petroleum and coal materials, soil used for road, building, dam and airfield construction - used to reject wood plates having excessive moisture or knot in manufacturing pencils - dose from 30 mCi Am-241/Be Shielded: <10 mrem/h on surface Unshielded: <1 mrem/h at distance greater than 25 cm

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Continuous Chemical Analysis	Measuring coal ash: 40 mCi Tl-204 coal sensor: 100 mCi Am-241 mine surveying: up to 500 mCi Co-60 Some on-stream analyzers: 20 mCi Sr-90 or Pm-147 50 mCi Sb-124 analyzers	Chemical analysis of raw materials and impurities in products in Mining and Quarrying, Food and Beverage, Chemical, Petroleum and Coal, Glass and Ceramic and Basic Metal Industries	- conveyor belt analysis to determine naturally-occurring radioactive minerals (e.g. potash) - used as a coal sensor and in mine surveying, in elemental food analysis, measuring coal ash content, analyzing ores and mine gases - measuring chlorine in chlorinated hydrocarbons, potassium in fertilizers, Co, Pb, N, O, Cl and F in petroleum, sulphur in hydrocarbons, boron in boron compounds, lead in gasoline, glass/resin ratios in glass epoxy, K, Pb and Se in glasses, composition of furnace melts and exhaust gases, carbon to hydrogen ratios in petroleum products, continuous dust measurement in air
- Borehole Logging	Coal Mining: 5-10 mCi Co-60 or Cs-137 Activation logging for bauxite, fluoride, Cu and Mn ores: 3-5 Ci Po-210/B or Po-210/Be	Mining and Quarrying, Petroleum and Coal, Mineral Processing, Phosphate Mining	- similar to density and moisture gauges - gives direct information on the nature and composition of underground strata - a source and detector are lowered into the borehole

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
Borehole Logging (cont'd)	Beryllium Photoneutron logging: 20-150 mCi Sb-124 Boron logging: 2 Ci Po-210/B		and depth versus detector output are charted - core analysis by γ-log runs - specialist companies perform this application
- Viscosity Measurement		Medical and Pharmaceutical Industries	- control of viscosity of ointments, creams, etc.
- Weighing Measurement	1 Ci Cs-137	Chemical and Chemical Products	- packaging correct weight of detergent and other products in boxes
- Tire Pressure Detectors		Automobile Industry	
- Area Measuring			
- Delay Devices			- functions of time and radio-active delay
- Electron Microscope	Uranyl acetate	Laboratory Equipment	- used as a positive and negative stain and for shadowing
- Fluorescence Spectrometry	Analysis of cement raw mix: Po-210 and H-3/Ti source calcium in Kiln: Fe-55 Iron, Nickel, Copper and Zinc Powdered Ore Analysis: 30 mCi Pu-238	Chemical analysis used in Mineral, Cement, Photographic Industries, Police Work, Antiques, Paintings and Archaeology	- used in alloy analysis, detecting gold, diameter measures of tungsten, moly-bdenum and copper wires - metalliferous mineral explora-tion and development uses and uses in seabed exploration - calcium in kiln feed, Al, Si, Ca and Fe in raw mix

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION A: GAUGING & RADIOGRAPHY (cont'd)			
- Fluorescence Spectrometry (cont'd)			- determining age and validity of articles of interest - identifying bullet holes and measuring silver content of photographic emulsions - used in coating thickness measuring - analysis of powdered ore
SECTION B: TRACING			
- Product Identification and Radiometric Dating		Glass and Medical and Pharmaceutical Industry	- identification of special products, code numbers and labels by activation analysis - identification of glass articles as to quality and manufacturer e.g. lens
- Friction and Wear Studies	Sources in Tire Fabric: Tl-204 S-35	Pulp and Paper and Rubber Industries	- measuring rates of attrition - useful in research and new designs where tracers are used to show periodic irregularities in weight and thickness due to equipment - tracing tire wear - corrosion, erosion in pipes and vessels
- Mixing, Diffusion, Dispersion and Chemical Reaction Mechanism Studies	Diffusion studies: Rn-220 Rn-222 and radon daughters		- investigating the effectiveness of air mixing in a ventilated room - studying diffusion in the Troposphere

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION B - TRACING (cont'd)			
- Flow Rate Measurements, Flow Configura-rions, Leak Tests and Volume Measurements	Usually short-lived gamma tracers	General Industrial Application	- tracing expensive catalyst leaks
- Detection of Objects Blockages and Hidden Lines			- detecting voids in solids, gas pockets in liquid streams, entrainment of liquid in gas streams - indicating blockages in pulverized fuel feed pipes in Power Generating Stations
- Testing Separation Techniques			- testing techniques and efficiencies of filtration precipitation and electro-deposition
SECTION C: METAL ALLOYS			
- Magnesium Alloys	Elemental thorium	Aircraft	- high mechanical strength and light weight
- TD Nickel	Elemental thorium		- superior mechanical strength and corrosion resistence even at high temperatures (2400°F)
- Thorium Metal	Thorium metal		- gaseous discharge tubes and photoelectric tubes

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION C: METAL ALLOYS (cont'd)			
- Depleted Uranium	Produced from UF_6 tailings of uranium enrichment process for nuclear power reactors 99.8% U-238 0.2% U-235	Alloys used for counterweights, radiation shielding, ammunition, weapons and ballast	
SECTION D: RESEARCH			
- Sewage Treatment	Gamma radiation	Sewage Treatment Facilities	- disinfection with radiation
- Radiation Charging		Electrostatic Precipitators, Filtration and Wet Collection Systems	- charge fine particles using electric and magnetic fields with ionizing radiation
- Automobile Output and Exhaust	- uranium, radium or tritium series - weak radionuclides - uranium oxide catalyst on activated alumina	Automobile Industry	- increasing car output and purifying exhaust gas - ionize fuels hydrocarbon constituents
SECTION E: PROCESSES			
- Sterilization	Cobalt-60	Medical and Pharmaceutical and Food and Beverage Industries	- sterilization of sutures, syringes and other packaged items - sterilization of catgut - pasteurization - deinfestation of food of insects and parasites - 0.01 mrad kills insects - 0.1 mrad extends shelf life of fresh fruit and meat - 5 mrad kills viruses and resistant bacteria

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION E: PROCESSES (cont'd)			
- Polymerization		Polymer Industries	- modifying polymers through grafting and cross-linking
- Irradiation Catalysis			
- Chemical Grafting			
- Vulcanization		Rubber Industry	
- Wood Plastics and Textile-Plastic combinations		Textile and Polymer Industries	- modification of textiles and processing of plastics and elastomers
- Production of composite materials and surface coatings			- thickness gauge control
- Fission-fragment recoil energy for chemical processing			
- Metallurgy		Basic Metals Industry	- pig-iron, steel, non-ferrous metal melting and treatment
- High temperature refractories	Thorium oxide		

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION F: CONSUMER PRODUCTS			
- Colour TV sets	- high voltage rectifier - shunt regulation tubes - picture tube - all x-ray sources - (with solid-state circuitry, only picture tube is a source)	Consumer	Exposure - 1968 average dose @ 5cm = 0.043 mR/h - 1980 (estimate) @ 5cm = 0.025 mR/h
- Dinnerware and Glassware	- natural radioactive uranium in ceramic glazed dinnerware - 20% uranium in glaze	Consumer	- various combinations of uranium salts to obtain a variety of colours and fluorescences in glassware - no longer manufactured but still available - Dose estimates: Dishwasher 34.4 mrem/y Waiter 7.93 mrem/y Patron 0.18 mrem/y
- Tinted Eyeglasses		Consumer	
- False Teeth	Some K-40 0.001-0.044% uranium	Dentistry and Consumer	- uranium salts added to porcelain to match colouring and fluorescence of natural teeth

TABLE 2.16 (cont'd)

APPLICATION	TYPE OF SOURCE	COMMERCIAL OR INDUSTRIAL FIELD	DESCRIPTION
SECTION F - CONSUMERS PRODUCTS (cont'd)			
- False Teeth (cont'd)			- some potassium - 40 in porcelain α Dose: 137 mrem/y maximum β Dose: 0-1.19 rem/y uranium 0.08-0.2 rem/y K-40
- Kitty Litter	Ra-226	Consumer	
SECTION G: MISCELLANEOUS			
- Accelerators - Cyclotrons			
- Radar		Aviation, Consumer Product	- satellite communication systems - tracking radars - UHF TV transmitters
- Special Weapons		Aviation	- aviation - air traffic control - weather radars in aircraft

TABLE 2.17

Summary of Estimated Dose to Man
from Industrial or Commercial Uses

SOURCE	PERSONS AFFECTED	DOSE/DOSE RATE
Density Meters	Specific Personnel using such instrumentation	Maximum γ dose: 65 mrem/h Maximum neutron dose: 7 mrem/h
Moisture Gauges 30 mCi Am-241/Be	Specific Personnel using such instrumentation	Shielded: < 10 mrem/h on the surface Unshielded: < 1 mrem/h at distances greater than 25cm
Commercial Ionizing Smoke Detector 1 μCi Am-241 or 0.1 μCi Ra-226	General Population	10 inches away, 8 h/d: 0.5 mrem/y shielded 36.8 mrem/y unshielded
Tritium Dial Watch 200 mCi tritium	Owner	0.6 mrem/y
Radium Dial Watch	Owner	3 mrem/y
Nuclear-Powered Pacemakers	Owner	< 5 rem/y
2.5 Ci Pu-238	Family Non-family	7.5 mrem/y 0.2 mrem/y
Colour T.V. sets	General Population	0.5 mrem/h at 5 cm
Ceramic, Glazed Dinnerware 20% natural uranium in glaze	Dishwashers Waiters Patrons	34.4 mrem/y 7.93 mrem/y 0.18 mrem/y
False Teeth 0.001-0.044% uranium plus some K-40	Owner	α dose: 137 mrem/y maximum β dose: 0-1.19 rem/y due to uranium and 0.08-0.2 rem/y due to K-40.

15. Oziewicz, Stan. "Radiation emission questioned, smoke-detection units less hazardous than color TVs expert says." Globe and Mail, 19 June, 1976.

16. Pyrotronics Canada Ltd. "Pyrotronics ionization detectors are safe and save lives." News Release, N-4-76, 1976.

17. Roberts, K.J., and Vajdic, A.H. "Alternative methods of disinfection: how effective." Water and Sewage Works (September, 1974): 72-75.

18. U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The effects on populations of exposure to low levels of ionizing radiation." Washington, D.C.: National Academy of Sciences, 1972.

19. U.S. Atomic Energy Commission. "Radioisotopes in science and industry, special report." Washington, D.C.: U.S. AEC, 1960.

20. U.S. Environmental Protection Agency Office of Radiation Programs. "Radiation Protection Activities 1975". EPA-520/7-76-004. Washington, D.C.: U.S.EPA., Office of Radiation Programs, 1976.

21. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiation Protection Activities 1976." EPA-500/4-77-005. Washington, D.C.: U.S.EPA, Office of Radiation Programs, 1977.

22. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological quality of the environment." EPA-520/1-76-010. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1976.

23. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological Quality of the environment in the United States", 1977. EPA-520/1-77-009. Sept. 1977.

24. Uto, Akio "Method and apparatus for increasing output of car engine and purifying exhaust gas." U.S. patent 3.678.9080, July 25, 1972.

25. Personal Communication with Mr. K. Badham, AECL, March, 1978.

2.5 Inadvertent Sources

2.5.1 Emissions from Coal-Fired Power Plants

Coal is composed chiefly of carbon, hydrogen, and oxygen, with minor amounts of moisture and mineral impurities, including various radionuclides. On combustion, the trace elements in coal are transferred to slag, fly ashes, or gases. The major types of coal, in order of increasing carbon content, are: brown, lignite, subbituminous, bituminous and anthracite.(1)

The radiological content of coal has been a matter of considerable interest in recent years. Some authors have investigated the content of coal, fly ash and/or bottom ash (2,3,9,10,11,12). Others have investigated emissions of coal burning power plants, and compared the possible risks due to emission to those due to emission from a nuclear power plant (4,5,7,8).

In coal-fired power plants, elements entering the boiler in the coal stream are partitioned between a bottom ash (or slag) stream, and a flue gas stream containing fly ash and the vapours of volatile elements or compounds. A further partitioning of the flue gas stream takes place in the particulate emission control devices (electrostatic precipitators or scrubbers). These control devices remove larger fly ash particles with efficiencies typically ranging from 95 to 99.5%, but are less efficient for vapours and finer particles.

Ash from the boiler (the bottom ash) and ash removed by the precipitators are slurried with water and transported to ash holding ponds. Elements may be leached from the ash and enter the aquatic environment in run-off. The slurry water may be recycled rather than discharged. The small particles and vapours discharged to the atmosphere enter the terrestrial and aquatic environment by wet or dry deposition (9).

Tables 2.18 and 2.19 show representative radium, thorium and uranium content of coal and fly ash. A range of values is to be expected, since the coal source, collector efficiency and coal preparation methods vary. Most coal presently burned in North America is U.S. eastern coal, which tends to have a high sulphur content and a low radioactivity content (typically 1-3 ppm for uranium, thorium and radium). The average uranium and radium content of some reserves of low sulphur western coal is about 50 times higher than most eastern coals (7). Ontario Hydro uses about 99% of the coal burned in Ontario (13). This coal is mainly Appalachian in origin.

Klein et al. (9) did a mass balance on trace elements in a coal-fired power plant, and found three general classes of elements:

(i) Some were quite concentrated in fly ash compared to the slag, and were more concentrated in the ash discharged through the stack (the smaller particles) than in that collected by the precipitator (larger fly ash).

TABLE 2.18 (8)

Analysis of Radioactivity in Coal Ash (Radium and Thorium)
Concentration (pCi/g dry fly ash)

Sample	Ra-226	Ra-228	Th-228	Th-232
Appalachian coal ash	3.8	2.4	2.6	-
Utah coal ash	1.3	0.8	1.0	-
Wyoming coal ash	-	1.3	1.6	-
Japan coal ash	-	1.5	1.6	-
Alabama coal ash	2.3	2.2	2.3	-
TVA coal plants	4.25	2.85	2.85	2.85
Coal ash (Australia)	7.98	-	-	-
Coal fly ash Hartsville	2.3	3.1	-	3.1
Coal fly ash Colbert, TVA	3.1	6.9	1.6	6.9
Coal fly ash Widows Creek, TVA	1.6	2.7	2.8	2.7

Table 2.19

Analysis of Radioactivity in Coal Ash (Uranium)

Sample	Uranium Content	References
Pennsylvania Anthracite: Ash	1.55 ppm to 2.65 ppm	(11)
Appalachian subbituminous: fly ash	(U-238) 1.1 ppm	(12)
Southern Illinois and Western Kentucky:		
coal	2.18 ppm	(9)
slag	14.9 ppm	(9)
fly ash	30.1 ppm	(9) (before precipitator)

Table 2.20 (3)

Radium-226 Activity of Coal and Ash

Samples from Pyrmont Power Station, Sydney, Australia

Sample	pCi/g ash	pCi/g coal
Coal A	8.3	1.3
Coal B	4.7	0.8
Coal C	5.6	0.9
Ash A	9.3	-
Ash B fly ash from precipitators and bottom ash	5.4	-
Ash C	5.6	-
Stack Scrapings	5.6	-
Fly Ash - escapes precipitators	14.0	-

Table 2.21 (14)

Coal Consumption of Ontario Hydro in 1977
(Appalachian - most from West Virginia and Ohio - the Pittsburg Seam)

Station	Tons coal burned
Hearn	0.175×10^6
Lakeview	2.236×10^6
Lambton	2.9×10^6
Nanticoke	3.07×10^6
Thunder Bay	0.202×10^6
Total	8.584×10^6 tons

Table 2.22

Ash Content of Coal

Source	Ash Content	Reference	Comments
no origin given	13%	(8)	
Western Kentucky	11.4%	(9)	
Pennsylvania	9.5 to 12.8%	(11)	
Appalachian	9%	(12)	Estimate only

Average: 11% (average will be used since the reference for Appalachian coal is an estimate only)

(ii) Some showed little preferential partitioning between the slag and the collected or discharged fly ash. Thorium is in this group.

(iii) A group showing intermediate behaviour between the first two groups. Uranium is in this group.

Unfortunately, radium was not included in the mass balance. However, a study by Bayliss and Whaite (3) indicates that radium may tend to partition into the fine fly ash that escapes up the stack as well. (See Table 2.20) In another study, Moore and Poet (10), found that coal-fired power plants contributed significantly to radium-226 levels in the lower troposphere.

It is difficult to estimate how significant these releases might be. Some authors claim that more radioactivity is released by coal-fired plants than by nuclear reactors. (e.g. Einsenbud and Petrow (12)). Others say that nuclear reactors have more significant releases than coal plants (e.g. Martin and Harward (8)).

All authors admit that a comparison is difficult: "It is impossible to make a simple comparison of the effects of effluents from nuclear and fossil-fuel plants. Gas emissions from nuclear plants produce 'whole-body' exposure while radionuclides in fly ash present hazards to specific parts of the body. If the fly ash is insoluble, it lingers in the lungs; if it is soluble, it passes into the blood and settles into the bone tissues" (4).

Some authors tend to dismiss the radiological emissions of coal-fired power plants as insignificant when compared to other emissions from these plants. Whether or not this is a valid point is difficult to assess on the basis of available data.

The situation is complicated by the fact that the ash (both fly and bottom) collected from the plant may be used as an aggregate, for use in such things as building blocks or road surfaces, rather than being buried in pits.

Ontario Hydro burned approximately 8.6 million tons of Appalachian coal in 1977 (15). (See Table 2.21) No emission estimates were available from Ontario Hydro, but rough estimates can be made. From Table 2.18, the radionuclide content of Appalachian coal fly ash includes:

Ra-226,228:	6.2 pCi/g ash
Th-228,232:	2.6 pCi/g ash

Assuming an average ash content of 11% (Table 2.22), Ontario Hydro operations release an estimated 5.3 Ci/y radium-226 and 228, and 2.2 Ci/y thorium-228 and 232. This radionuclide content is distributed between ash for solid waste disposal and particulate airborne emission.

Future estimated coal consumption by Ontario Hydro is:

1978 - 9 million tons/year
1982 - 13.5 million tons/year

Beginning in 1979, there will be a shift to western bituminous coal from the foothills region in Alberta and British Columbia. This coal will be used primarily for blending purposes at Nanticoke (14). No information is available on radioactivity in this coal.

According to Guimond (17), other radionuclides of potential interest in estimating the radiological significance of coal utilization are short-lived radon daughters, polonium-210 and lead-210.

References - Coal-Fired Power Plants

1. "Kirk - Othmer Encyclopedia of Chemical Technology", 2nd ed. s.v. "Coal".

2. Barber, D.E., and Giorgio, H.R. "Gamma-ray activity in bituminous, subbituminous and lignite coals." "Health Physics". 32 (February 1977):83-88.

3. Bayliss, R.J. and Whaite, H.M. "A study of the radium alpha-activity of coal, ash and particulate emission at a Sydney power station." "Air and Water Pollution." 10 (1966):813-819.

4. Hill, Philip G. "The social costs of electric power generation." Submitted to the Royal Commission on Electric Power Planning. Toronto: Ontario Gov't., 1977.

5. Lave, L.B. and Freeburg, L.C. "Health effects of electricity generation from coal, oil, and nuclear fuel." "Nuclear Safety" 14 (September-October 1973): 409-428.

6. Natusch, D.F.S.; Wallace, J.R.; and Evans, C.A. "Toxic trace elements: preferential concentration in respirable particles." "Science" 183 (January 1974): 202-204.

7. Gotchy, R.L. "Health effects attributable to coal and nuclear fuel cycle alternatives, draft." NUREG-0332. Washington, D.C.: U.S. Nuclear Regulatory Commission, Division of Site Safety and Environmental Analysis, 1977.

8. Martin, J.E.; Harward, E.D.; and Oakley, D.T. "Radiation Doses from Fossil Fuel and Nuclear Power Plants." In: Berkowitz, D.A. and Squires, A.M. (eds.) "Power Generation and Environmental Change", MIT Press, Cambridge Mass, 1971.

9. Klein, D.H. et al. "Pathways of Thirty-seven Trace Elements Through Coal-Fired Power Plant." "Environmental Science and Technology." 9 (October 1973): 973-979.

10. Moore, H.E. and Poet, S.E. "Background Levels of Ra-226 in the Lower Troposphere." "Atmospheric Environment" 10 (1976): 381-383.

11. Chow, T.J. and Earl, J.L. "Lead and Uranium in Pennsylvania Anthracite." "Chemical Geology" 6 (1970): 43-49.

12. Eisenbud, M. and Petrow, H.G. "Radioactivity in the Atmospheric Effluents of Power Plants that use Fossil Fuels." "Science" 144 (April 1964):288-299.

13. Dr. H. Aikin, Ministry of Labour, telephone conversation, March 1978.

14. Mr. Kaine, Ontario Hydro, telephone conversation, March 1978.

15. Mr. Featherby, Ontario Hydro, March 1978.

16. U.S.E.P.A. "Compilation of Air Pollutant Emission Factors, 2nd ed." U.S.E.P.A., Office of Air and Water Programs, North Carolina, April 1973.

17. Guimond, J.G. and Fitzgerald, J.E. "The Radiological Implications of Increased Coal Utilization." "Tenth Midyear Topical Symposium of the Health Physics Society, Northeastern New York Chapter, Saratoga Springs, New York, 1976." Rensselar Polytechnic Institute, Troy, 1976.

2.5.2 Emissions from Oil-Fired Power Plants

The amount of radioactive material released by oil-burning power plants is almost undetectable (1). One analysis of radium and thorium content (2) showed levels in oil fly ash to be only 10% of the levels in coal fly ash (see Table 2.23). As such, oil-fired power plants are not thought to be significant sources of radioactivity. In addition, it is unlikely that oil will be an important fuel for electrical generation in the future.

TABLE 2.23(3)

Radioactivity in Oil Fly Ash

Sample	Concentration (pCi/g dry fly ash)			
	Ra-226	Ra-228	Th-228	Th-232
Venezuela petroleum ash	0.21	0.49	0.67	-
Oil fly ash Turkey point	0.18	0.17	0.82	0.17

References - Emissions from Oil-Fired Power Plants

1. Lave, L.B., and Freesburg, L.C. "Health effects of electricity generation from coal, oil, and nuclear fuel". "Nuclear Safety" 14 (September -October 1973): 409-428.

2. Hill, Philip G. "The social costs of electric power generation". Submitted to the Royal Commission on Electric Power Planning. Toronto: Ontario Govt., 1977.

3. Martin, J.F., et al. "Radiation Doses from Fossil-Fuel and Nuclear Power Plants." In: Berbowitz, D.A. and Squires, A.M. (ed's) "Power Generation and Environmental Change", MIT Press, Cambridge, Mass. 1971.

2.5.3 Fallout

The term fallout refers to the injection of radioactive debris into the atmosphere and its subsequent deposition on the ground from large nuclear explosions in the atmosphere for weapons testing, primarily during the years 1961, 1962. Continental testing in the United States also took place in the periods 1951-57, but these were mostly low yield nuclear devices. Additional atmospheric testing by France and China since 1962 has not greatly increased the resultant radiation exposure to man (1). For example, atmospheric testing from 1962 through 1970 added about 5% to the total strontium-90 produced previous to 1962. The long half-lives of the fallout radionuclides (e.g. 30.2 y for cesium-137) and their long-term deposition from the upper atmosphere are responsible for on-going population exposure even though atmosphere testing is now severely reduced. The present annual whole-body dose from global fallout in the United States is estimated at 4.3 mrem/y (2). This is expected to increase to about 4.9 mrem/y by the year 2000 (2).

As is the case with natural radioactivity, radioactive fallout provides an external dose component from gamma emitters and an internal component from emitters taken up by the body. Table 2.24 gives the mean dose commitment in the United States. This is the total dose that will be received from these sources by individuals up to the year 2000.

Cesium-137 is now the major source of external exposure although shorter-lived radionuclides such as iodine-131 may have contributed greater exposures, particularly during the continental tests. The external dose commitment from cesium-137 ground deposition has been estimated for the period 1950-1970 to be 134 mrads for the Northern Hemisphere (2).

Internal exposure is mainly due to strontium-90 and cesium-137. Input of strontium-90 by milk ingestion is a well-known pathway to man which, in 1976, resulted in a bone marrow dose of about 3 mrem to residents of Canada (3). Cesium-137 results in an estimated internal dose commitment of 19 mrads on a population-weighted basis for the Northern Hemisphere (2).

In addition to the above-mentioned fallout radionuclides, carbon-14 and tritium (hydrogen-3) inventories were greatly increased over natural levels by weapons testing (by factors of approximately 2 and 300 respectively (1)). However, these radionuclides still result in much less radiation exposure than that from cesium-137 and strontium-90. Tritium decays with a half-life of 12.3 years and the carbon-14, like that produced naturally, will eventually be transferred to the deep oceans where it will be relatively unavailable as a source of radiation exposure.

References - Fallout

1. U.S. National Council on Radiation Protection and Measurements. "Natural Background radiation in the United States." NCRP Report No. 45. Washington, D.C.: NCRP, 1975.

2. U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological quality of the environment in the United States, 1977." EPA-520/ 1-77-009. September 1977.

3. Vasudev, P. et al. "Environmental Radioactivity near Canadian Nuclear Reactor Sites." "Annual Conference of Canadian Nuclear Association, Montreal, 1977." Radiation Protection Bureau, Dept. of National Health and Welfare, Ottawa.

4. United Nations Scientific Committee on the Effects of Atomic Radiation. "Ionizing Radiation Levels and Effects, Vol. 1: Levels", United Nations, New York, 1972.

TABLE 2.24 (1)

Mean Dose Commitments (mrad) in the United States from Nuclear Testing through 1970

	Mean Dose Commitment
external	80
internal	
Sr-90, marrow	45
endosteal	65
Cs-137, gonads	15
Pu-239, lung	2
bone	0.2
I-131, thyroid	unknown
Kr-85, skin	0.02
H-3, gonads	2
C-14, gonads	12 (a)
Fe-55, gonads	< 1
red blood cells	3

(a) This is the dose commitment to the year 2000. The total dose commitment, to be delivered over many lifetimes, is 140 mrad.

2.5.4 Non-Uranium Mining

The mining, milling and disposition of the wastes of non-uranium ores are only recently being investigated from an environmental radiation perspective.

The mining of non-uranium ores in Ontario does not appear to be a problem in this respect. For example, a survey conducted in non-uranium mines in Ontario by the Mines Accident Prevention Association of Ontario in 1970-72 and 1975-76 indicated that radioactivity is virtually non-existent. Values measured in mine exhausts range from nil to .28 WL, with most in the .01 to .03 WL range (1). This is low, in comparison with the present Canadian standard of an average 0.33 WL for the active working areas of the mines (5).

The uranium and thorium content of phosphate ranges from about 5 to 267 pCi per gram and 0.4 to 4 pCi per gram respectively. Uranium and thorium series isotopes may also be present.

Phosphate mining and milling has proved to be a source of radioactivity in the U.S. Phosphate is not mined in Ontario. However, phosphate processing (wet or dry), products, effluents and wastes are of concern as sources of radioactivity in the environment.

Phosphate fertilizer is produced by a wet process, with gypsum as a by-product. This gypsum usually contains the bulk of the radium originally present in the phosphate rock. Most of the uranium and thorium originally in the phosphate goes into the phosphoric acid product, which is used to produce fertilizer. Some radium is also retained in the fertilizer. Thus, fertilizer produced from phosphoric acid, may serve to slightly increase background radiation levels of naturally occurring radioactivity in agricultural products.

Elemental phosphorus is produced in the dry or thermal process. Almost all of radium is retained by a calcium silicate slag which is a by-product of this process.

Thus, it would appear that most of the radium that enters these two processes (wet and dry) ends up in the waste products: slag and gypsum. These products are used in making wallboard and building blocks, and, in some countries, as soil additives.

No data is presently available for Ontario on any of these possible sources of radioactivity.

References - Non-Uranium Mining

1. Mines Accident Prevention Association of Ontario. "Surveys of Radioactivity in Non-Uranium Mines. Periods June 1970 to August 1972 and November 1975 to December 1976". MAPAO, Toronto, March 1977.

2. Guimond, Richard J., and Windham, Samuel J. "Radioactivity distribution in phosphate products, by-products, effluents, and wastes" ORP/CSD-75-3. Washington, D.C: U.S. Environmental Protection Agency, Office of Radiation Programs, Criteria and Standards Division, 1975.

3. U.S. Environmental Protection Agency. Office of Radiation Programs. "Radiological Quality of the Environment in the United States, 1977". EPA-520/1-76-010, Sept. 1977.

4. Windham, Sam; Partridge, Jennings and Horton, Thomas. "Radiation dose estimates to phosphate industry personnel". Washington, D.C: U.S. Environmental Protection Agency, Office of Radiation Programs 1976.

5. "Atomic energy, control regulations", Canada Gazette Pt. II, 112 (January 1978): 406-411.

6. "Mid-year topical symposium of the Health Physics Society, Northeastern New York Chapter, 10th, Saratoga Springs, N.Y., 1976." Troy, N.Y.: Rensselaer Polytechnic Institute, 1977.

2.5.5 Transportation

Transportation of radioactive substances by air, rail, and truck is a source of radiation exposure to the general population. This exposure is almost totally due to external gamma radiation, although the release of radioactivity as a result of accidents could possibly cause internal exposure.

The majority of the shipped packages of man-made radioactivity contain radiopharmaceuticals. For example, at Dorval Airport in Montreal, (through which much of the imported radiopharmaceuticals are shipped), 50 percent of all the shipments and 90 percent of all the radioactivity is molybdenum-99 (1). In the United States, three materials: molybdenum-99, technetium-99m and iodine (I-123, -125 and -131) accounted for over 75 percent of the packages shipped in 1974 (2). The remaining shipments included other radiopharmaceuticals, iridium-192, research sources and spent fuel.

The total annual population exposure resulting from normal transport of radioactive materials is considered to be very small. No Canadian estimates of such exposure are known but in the United States transportation annually results in about 9600 person-rem of exposure (2) or less than 5×10^{-3} rem/person. The largest fraction of this exposure (~ 70 percent including 45 percent from molybdenum-99) results from shipment of medical-use radionuclides, with industrial shipments (~ 20 percent) and spent fuel shipments (~ 10 percent) making up the remaining portion. In Ontario, the spent fuel portion would be lower because at present spent fuel from commercial reactors is stored on site.

The largest population exposure is considered to be from truck transportation because of the long exposure times at low levels of the large numbers of people surrounding transport links. Individual exposures are generally only slightly above background (2). If averaged over the number of persons exposed, normal transportation results in some 0.5 mrem/y in the United States compared to about 100 mrem/y of background radiation. Eichholz (3) outlines some methods of calculation of exposures from routine shipments.

Estimates for the exposure from the transport of natural radionuclides (such as yellowcake from uranium mills, and uranium dioxide from the refinery to fuel fabrication to a CANDU reactor) have not been identified in this study.

As previously mentioned, transportation accidents could increase radiation exposure to the individuals involved. There is very little Canadian data to assess this potential hazard, although Ontario Hydro has estimated the dose resulting from a spill of tritiated water during transportation (4). Tritiated water is heavy-water that has become radioactive by its use in a reactor. In the United States, of the only 300 accidents reported in the past 25 years (as of 1976), 30 percent involved release of radioactivity and all of these were from transportation of medical and industrial radiochemicals (5). No deaths or perceptible injuries were caused. To date, there have been no releases from spent fuel shipments in Canada or the United States (6).

References - Transportation

1. AECB, private communication, March 1978.

2. U.S. Nuclear Regulatory Commission. "Draft environmental statement on the transportation of radioactive material by air and other modes", NUREG-0034. Washington, D.C.: U.S. Nuclear Regulatory Commission, 1976.

3. Eichholz, G.E. "Environmental aspects of nuclear power". Ann Arbor, Michigan: Ann Arbor Science, 1976.

4. Walsh, M.L. "An estimate of the dose resulting from a spill of tritiated heavy water during transportation". M.S.D.-70-2. Toronto: Ontario Hydro, 1970.

5. U.S. Environmental Protection Agency. "Radiological quality of the environment". EPA 520/1-77-004, Washington, D.C.: EPA, 1977.

6. Canadian Nuclear Association. "The role of nuclear power in Ontario; submission to the Royal Commission on Electric Power Planning". Toronto: Canadian Nuclear Assoc., 1976.

2.6 Discussion

As noted previously, naturally occurring sources of radiation exposure are by far the most significant contribution to the typical individuals' annual radiation dose. The next most important source of radiation expsoure is due to medical diagnosis or therapy. Man-made or man altered sources of radiation exposure account for a relatively small fraction of an individuals total annual population dose.

Effluent Controls 3

Introduction

Within each sector of the nuclear fuel cycle, extensive precautions are taken to minimize the release of radionuclides through air and water pathways, and to contain solid radioactive wastes in a secure fashion. Air cleaning devices, and general approaches to the control of water-borne radionuclides in nuclear fuel cycle operations are discussed in this chapter. The following discussions consider those facilities which handle the largest inventories of radioactive substances; namely uranium mine/mill complexes, refineries, fuel fabrication facilities and CANDU nuclear reactors, all of which are present in Ontario.

The radionuclides identified as being of primary interest in these various facilities are:

Uranium mine/mill	-	Natural uranium, Radium-226
Uranium refineries	-	Natural uranium
Uranium fuel fabrication	-	Natural uranium
CANDU reactors	-	Fission and activation products (especially iodine-131, noble gases, and tritium)

3.1 Air Pollution Control

3.1.1 General

Air cleaning devices remove contaminants from a gas stream and thus decrease the quantity of material that enters the receiving environment. Contaminants can be classed as either particulates or gases, and for each class there may be several control techniques with varying degrees of removal efficiency. In the following sections, the equipment commonly used is described and the factors influencing selection are noted.

In addition to conventional requirements for air cleaning equipment, applications involving radioactive emissions impose three further constraints:

(a) High efficiency is required due to the extremely low tolerances for the amount and concentration of stack effluents, the valuable nature of the materials handled and in some instances, the accountability of radioactive materials.

(b) Low maintenance is of special importance. Low frequency of maintenance, and speed and ease of maintenance operations will reduce worker exposure. In some instances, low residual buildup of material in the air cleaning device is a factor since excessive buildup will increase radiation exposure and thus reduce allowable working time.

(c) Efficient waste disposal is required due to the inability to dispose of appreciable amounts of radioactive materials either by air, water, or land. For example filters loaded with radioactive dust could require incineration to reduce the volume of material disposed in special burial grounds. The incineration in turn would require a fume scrubber or wet collector which can result in a contaminated water effluent requiring further chemical treatment.

With these factors involved, it is necessary to select a dust collecting device which will yield required efficiency without causing too much difficulty in either maintaining the equipment or disposing the collected material.

3.1.2 Particulate Removal Equipment

The following devices have been identified as applicable for particulate control in the nuclear fuel cycle:

(a) Fabric Filters (Baghouses)
(b) Wet Collectors (Scrubbers)
(c) Sintered Metal Filters
(d) Absolute Filters

The factors influencing the selection of this equipment include concen-

tration and particle size of contaminant, degree of removal needed, characteristics of gas stream, characteristics of contaminant, method of disposal, and cost.

Fabric Filters (Baghouses)

Fabric filters are high efficiency collectors capable of removing a wide size range of particles from a low velocity gas stream. The fabric filter acts in the same manner as a vacuum cleaner; however, dust laden air may be pulled or pushed through the filter material. The removal is accomplished through the buildup of a surface matte of material on the filter bag surface. As the layer increases the filter becomes more efficient. However, the pressure drop increases to the point where collection is decreased and cleaning is needed. Typical removal efficiencies are shown in Table 3.1.

Bag cleaning can be achieved by means of mechanically shaking the bag support frames or by reverse flow (either by reversing the gas stream to be treated or by providing a flow of compressed air). The reverse flow systems either inflate or collapse the filter media, thereby dislodging the filter cake.

The usual fabric is a specially woven cotton, although wool, paper, glass cloth and synthetic fabrics may be used in certain applications. In recent years glass cloth has come into wide use because of silicone treatment of the glass fibers and employment of reverse flow techniques for cleaning. Silicone treatment provides a lubricant between fibers and increases fabric life. Glass cloth is generally used in reverse flow collectors for high temperature gas streams and special applications where conventional fabrics are unsatisfactory.

Fabric collectors are limited to air conditions dry enough to prevent condensation or free moisture deposition on the fabric. With hygroscopic materials, there will be a bonding tendency between particles and fabric under high relative humidity even though no condensation takes place. Maximum recommended temperature for cotton fabric is 180°F, for wool 200°F. Higher temperatures can be handled by using synthetic materials including nylon or orlon fabrics as well as glass cloth and occasionally, fine metallic mesh. The synthetic fabrics may be used up to 275°F while glass cloth is acceptable to 550°F. Equipment cost is increased considerably with these special media.

For some applications, two baghouses in series are provided. The second baghouse will have reduced efficiency due to low input dust loadings, however, baghouse maintenance can be performed while maintaining particulate removal efficiencies, and the second baghouse provides back-up in case of bag failure.

Baghouses are widely used in the nuclear fuel cycle and find application in uranium mills, refineries, and fuel fabrication facilities.

Wet Collectors (Scrubbers)

Wet collectors are usually selected when: a) high temperature and moisture-laden gases prevent the use of fabric filters; b) water offers the more convenient method of disposal of collected material either due to plant facilities or to prevent creating a secondary dust hazard if collected material is handled dry; or c) when exhaust air contains corrosive gases or vapours requiring special materials of construction.

Wet collectors are commercially available in many different designs, and show a wide range of performance. Efficiency is a function of total energy input per cfm whether the energy is supplied to the air or the water. This relationship applies only when the energy is expended in promoting the gas-liquid contacting process. Typical removal efficiencies are shown in Table 3.1. By means of humidification, wet collectors have the ability to cool and reduce the volume of the gas stream leaving the collector. A number of configurations are available:

Chamber or Spray Tower:	Utilizes impaction of the dust particles on liquid droplets created by spray nozzles. These droplets are separated from the air stream by centrifugal force or impingement on water eliminators.
Wet Centrifugal:	Utilize centrifugal force to accelerate the dust particles for impingement upon a wetted collector surface.
Wet Dynamic Precipitator:	Utilize water sprays within a fan housing and obtain precipitation of the dust particles on the wetted surfaces of an impeller with special fan blade shape.
Venturi:	Utilize a venturi-shaped constriction to establish high gas velocities in the venturi throat. Water is supplied at or ahead of the throat of the venturi.

Wet collectors for particulate removal find application at uranium mills, refineries and fuel fabrication facilities.

Sintered Metal Filters

Porous metal filters with up to 50% of their volume consisting of interconnecting voids or pores are made by sintering pre-alloyed metal powders of selected particle sizes in a controlled-atmosphere furnace. The powdered metal particles (e.g. stainless steel, inconel, monel, nickel, silver and high nickel/molybdenum alloys) fuse at their points of contact, resulting in a bond with a homogeneous crystalline structure. Filters are available with absolute filtration ratings of 1.0 μm (diameter of the largest hard spherical particle that will pass through a

TABLE 3.1

Collection Efficiency of Particulate Control Equipment for Various Particulate Size Ranges (microns)(8)

Collector type	Efficiency, % Overall	0-5	5-10	10-20	20-44	>44
Baghouse	99.7	99.5	100	100	100	100
Spray tower	94.5	90	96	98	100	100
Self-induced spray scrubber	93.6	85	96	98	100	100
Disintegrator scrubber	98.5	93	98	99	100	100
Venturi scrubber, 30-in pressure drop	99.5	99	99.5	100	100	100
Wet impingement scrubber	97.9	96	98.5	99	100	100

filter under specified test conditions). However, because dust particles may impinge on surfaces as the gas passes through the filter, the removal rating is higher than the mean pore size. A filter with an absolute rating of 1 μm has a nominal filtration rating (98% removal by weight) of 0.4 μm diameter particles.

Sintered metal filters can withstand much higher temperatures than fabric filters and thus are used at elevated temperatures (to 900°F) where high efficiency of removal is required. Metal filters can also offer improved corrosion resistance, and high pressure capabilities. Filter cleaning can be performed at predetermined pressure drops by backflushing the filters with high pressure air or inert gases.

Sintered metal filters are an established control device in use at uranium refineries.

Absolute Filters

High Efficiency Particulate Air (HEPA) filters have been used for many years in the nuclear industry to effectively remove radioactive particulates from air streams. A modular HEPA filter has a cross section of 2 ft by 2 ft, a depth of 1 ft, and a capacity of about 1000 cfm (2). Filter modules are formed into banks to achieve the required filtration capacity. The filter medium is a pleated mat of woven fiberglass and consists of very fine (submicron) fibres in a matrix of larger (1-4 micron) fibers. The filter paper is extremely weak and fragile. By definition, a HEPA filter is an expendable (single-use), extended-medium, dry filter having a minimum particle removal efficiency of no less than 99.97% for 0.3-micron particles (3).

The following considerations apply to the design and normal operation of HEPA installations (4):

i) A high efficiency for the filters can be ensured by installing them in such a manner that all of the gas to be treated passes through the filters. Continuous pressure drop measurements can indicate whether the filters are plugging or have been ruptured.

ii) HEPA filters are intended primarily for submicron particulate removal. Thus they have a low dust capacity and may plug rapidly. Consequently, HEPA filters must be preceded by high-efficiency dust collectors.

iii) Excessive moisture can impair the efficiency of the filter. It is mandatory to remove all entrained moisture or to heat the air to above the dew point.

HEPA filters find application at fuel fabrication facilities, nuclear reactor off-gas management systems, certain research facilities (e.g. Chalk River Laboratory) and other specialized applications.

3.1.3 Gaseous Removal Equipment

It is worth noting that in most instances in the nuclear fuel cycle except the nuclear reactor, control of airborne radioactivity is almost solely achieved by means of particulate removal. Absorption devices such as packed towers, tray towers (scrubbers), and venturi scrubbers are used to remove non-radiological chemically reactive gases at uranium refineries (NOx, HF). The only identified use of scrubbing devices for radiological gaseous emission control at front-end fuel cycle operations is the use of a KOH fume scrubber at refineries to control UF_6 gas discharge in the event of an emergency.

In the front end of the fuel cycle, the principal gaseous radionuclide of concern is radon-222. Radon removal techniques are, however, only experimental. A number of gaseous radionuclides, principally iodine and noble gases are produced in a nuclear reactor. The nuclear reactor can also give rise to an airborne tritium discharge (as tritiated heavy water and hydrogen). Specific gaseous radionuclide removal techniques are briefly considered below.

Radon Removal

Several techniques have been studied to remove radon from ventilation air (5). These techniques include:

- Ambient temperature two bed charcoal adsorption
- Low temperature single bed charcoal adsorption
- Molecular sieve adsorption
- Cryogenic condensation
- Chemical reaction with molecular sieves
- Organic fluid absorption
- Semi permeable membranes
- Centrifuge

Costs for these systems have been estimated for mine ventilation and range from \$0.067/1000 scf for ambient charcoal adsorption to \$1,700.00/1000 scf for centrifuge (U.S. dollars 1975) (5). The least expensive option, ambient charcoal adsorption, was sized for a radon retention time of 1 hour (99% removal), and thus the system would be cycled, returning >90% of the retained radon to a waste gas stream on purge. These systems were studied for removal of radon gas in underground mines, and it was concluded that supplying additional ventilation was cheaper than radon removal with conventional ventilation. The study concluded that although the removal of radon from mine air is technically feasible, it is very expensive, and probably will not be widely used in the near future (5).

Activated Carbon Adsorbers

Adsorbers remove contaminants by collection on a solid. No chemical reaction is involved as adsorption is a physical process where molecules of a gas adhere to surfaces of the solid adsorbent. Activated carbon or molecular sieves are popular adsorbents.

Activated carbon adsorbers, tightly packed beds of carbon granules, are the most satisfactory devices available at present for trapping gases such as iodine-131 in nuclear reactor ventilation systems. Activated carbon is produced from charcoal, and is activated by controlled heating in a steam atmosphere to drive off organic matter and generate large internal surfaces for adsorption (700-1800 m^2/g)(2).

Important properties of a nuclear adsorption system include efficiency for trapping gases (radioiodine), holding capacity or breakthrough capacity, desorption characteristics (retentivity), air flow capacity and air flow resistance. Efficiency is a function of many parameters, however in general, the efficiency of nearly any good grade activated carbon will be at least 99% for elemental iodine under most operating conditions. Efficiencies are reduced somewhat when iodine loading in the gas stream is <0.01 mg/m^3 (6). Holding capacity will decrease with time due to physical and chemical poisoning by trace impurities which occupy active sites. Desorption is not a significant problem at temperatures below 250°F as long as the quantity of iodine held in the bed is less than the retentivity limit of the bed (typically 35-45% of the holding capacity). At room temperature, desorption of iodine from charcoal is about 0.001%. Other techniques which have found use for radioiodine removal include liquid scrubbers and silver based zeolite molecular sieves.

Noble Gas Removal

Several isotopes of the noble gases krypton and xenon occur by fission in the nuclear fuel. Their appearance in effluent streams results from fuel cladding failure. In addition, argon-41 can result from activation of air in the vicinity of the reactor core. In CANDU reactor systems, radioactive noble gases are collected from three sources: from the bleed condenser for degassing the heat transport coolant; from the gas collection system on the fuelling machine, and from the fuel transfer chamber (release during transport from the fueling machine to the spent fuel bay).

The currently practiced method of routinely minimizing the discharge of noble gases to the environment or after an upset is by holdup for radioactive decay followed by controlled discharge.

Ambient temperature charcoal adsorption is currently being used to delay noble gas releases from CANDU reactors. The adsorption process provides an appreciable holdup time for the radioactive noble gases, thus facilitating decay to particulate daughters that should be retained in the charcoal element acting as a filter. For CANDU systems, a decontamination factor of 40 based on xenon-133 can be achieved within a holdup time of 28 days. The design objective is to maintain atmospheric discharges of noble gases below 0.6% of the derived release limit (7).

Other techniques which have been proposed for noble gas treatment include (6):

- selective adsorption using molecular sieves
- low temperature activated carbon adsorption (improved efficiency at liquid N_2 temperatures)
- cryogenic distillation
- fluorocarbon absorption
- selective permeation
- underground disposal in suitable geologic formations

Several of these proposed techniques are designed to recover the noble gases as opposed to holdup decay. This is likely prompted by concern for release of the long-lived gas krypton-85 (half life 10.7 y) which is not removed with holdup decay treatment. The impact of global increases of krypton-85 is a subject of current concern and debate in the U.S.A.(6).

Heavy Water Vapour Recovery Systems

Systems are incorporated in CANDU reactors to minimize the loss or downgrading of heavy water which escapes from the heat transport and moderator systems. Vapour recovery systems maintain a dry atmosphere in areas subject to D_2O leakage by means of adsorption driers.

D_2O vapour recovered in these adsorption systems is in turn recovered by reactivation condensers. The recovered D_2O is segregated according to degree of downgrading and tritium activity and then forwarded to heavy water cleanup and upgrading systems prior to recycle.

Heavy water is also recovered from effluent streams directed to the off-gas management system by means of glycol condenser/separators and freon refrigeration systems prior to iodine/noble gas treatment. In the case of the gas stream from the bleed condenser, the treated stream consists primarily of deuterium gas and thus is not vented, but rather recycled via a deuterium addition system.

3.2 Water Pollution Control

The control of waterborne radioactive emissions is highly integrated to internal process recycle steps. By recycling process streams, and using effluents in place of fresh water for such operations as chemical make-up, losses of residual levels of radionuclides can be minimized. Techniques employed in various operations in the fuel cycle are briefly discussed in this section.

3.2.1 Uranium Mine/Mill

Water used in the mine for dust control and cleanup becomes acidic as it passes through the mine workings, leaching uranium and other constituents from the ore. Mill practice dictates that mine water be used preferentially for process water makeup, thereby ensuring effective recovery of its uranium content. Within the mill, steps are taken to promote virtually complete recycle of the water used to carry the uranium from ion exchange to yellowcake precipitation, and to utilize portions of the barren leaching liquor for tailings separation. The tailings discharge is the prime water discharge point. Prior to disposal, this tailings slurry is neutralized to inhibit bacterial acid generation, and precipitate heavy metals including the radionuclides of thorium and lead. It is worth noting that both uranium and thorium can be precipitated quite effectively by means of pH control. In fact, this property forms the basis of uranium recovery. Finally, the water effluent from the tailings basin is treated for radium removal.

Dissolved radium removal from uranium mill tailing pond effluent is accomplished with the addition of barium chloride. The barium combines with sulphate which is present in the effluent (from sulphuric acid leaching in the mill circuit) to form barium sulphate which then precipitates out of solution. Since radium has chemical properties similar to those of barium, a co-precipitation results. The barium-radium sulphate precipitate is initially formed as a fine colloid which upon aging aggregates to form larger crystals. Thus settling basins are provided with sufficient retention time to promote floc formation and improved settling. The efficiency of the process is influenced by barium chloride addition rates (typically 10-25 mg/l), degree of mixing (to a moderate degree for effective chemical mixing and floc growth), and retention time. Chemical flocculant can also be added where necessary to accelerate settling.

This treatment technique has been used to successfully remove over 99% of the dissolved radium from effluents.

The long-term control of radionuclide discharge from post-operational tailings ponds is a subject of current investigation.

3.2.2 Uranium Refinery/Fuel Fabrication

Substantial amounts of water recycle, coupled with a uranium recovery system (via pH control), and provisions for neutralization of process

waste water streams effectively control water-borne uranium losses. In fuel fabrication, process water requirements are not substantial, and control of uranium losses is achieved by the removal of insoluble UO_2 by means of settling/centrifuge. Neither refining or fuel fabrication generate significant water-borne radionuclide releases.

3.2.3 Nuclear Reactor

Control of water-borne tritium losses is highly integrated to the control of heavy water loss. The general liquid waste processing system for CANDU reactors is briefly described below.

CANDU Liquid Waste Processing System

Due to the economic penalty associated with the loss of heavy water, a great deal of effort is spent in all stages of design and operation to incorporate heavy water recovery and recycle systems into the normal operating cycle. Both moderator and heat transport system heavy water inventories are purified by ion exchange cleanup systems to maintain D_2O purity, adjust levels of soluble poisons, and limit the buildup of corrosion products thereby minimizing activation of these impurities such as cobalt-60. The design level of impurity concentration is less than 1 mg/l. Disposable paper filters are also incorporated to remove insoluble impurities.

The D_2O management system is provided to recover and upgrade heavy water collected from the vapour recovery system (adsorption) and liquid recovery system (spills and leaks from moderator and heat transport systems). The collected material is purified to remove most impurities except light water. Charcoal filters remove organic impurities, and ion exchange columns remove lithium, boron, iron, nitrate, other corrosion products and fission products such as cesium and the radioiodines. Cleanup is followed by D_2O upgrading by means of packed column distillation. The input is an average 62% D_2O producing a bottom stream of reactor grade (99.8%) D_2O and an overhead stream with <2% D_2O.

Finally, an active waste management system is provided to handle liquid waste streams such as D_2O upgrading overhead, laundry and decontamination wastes, laboratory rinse and reactor/service building floor drains. These wastes are collected, analysed and finally released in a controlled fashion to the condenser cooling water in such a manner to maintain levels below 1% DRL (7). Provisions can also be made to treat active wastes, if warranted, prior to release - e.g. final ion exchange polishing of the more active waste streams.

References - Effluent Controls

1. Pall Corporation, "The Pall Cleanable Filter Guide", 1976.

2. Burchsted, C.A. et al, "Nuclear Air Cleaning Handbook", Report prepared for U.S. ERDA by Oak Ridge National Laboratory, Second Edition, 1976.

3. International Atomic Energy Agency, "Treatment of Air-borne Radioactive Wastes" August, 1968.

4. Sears, M.B. et al, "Correlation of Radioactive Waste Treatment Costs and the Environmental Impact of Waste Effluents in the Nuclear Fuel Cycle - Conversion of Yellowcake to Uranium Hexafluoride. Part 1. The Fluorination - Fractionation Process." Oak Ridge National Laboratory, Sept. 1977.

5. Arthur D. Little, Inc., "Advanced Techniques for Radon Gas Removal" Report Prepared for U.S. Department of Interior, Bureau of Mines, May, 1975

6. Eichholz, G.G. "Environmental Aspects of Nuclear Power", Ann Arbor Science Publishers Inc., 1976.

7. Drolet, T.S. et al, "CANDU Radioactive Waste Processing and Storage", paper presented at ANS Winter meeting, Nov. 1975.

8. Perkins, Henry C., "Air pollution", McGraw-Hill, New York, 1974.

Environmental Pathways 4

Introduction

The ubiquitous nature of radioactivity has caused concern about the amounts of the various radionuclides that may result in radiation exposure to man either directly by irradiation from environmental contamination (external and inhalation) or indirectly through biological pathways (eg. food chains).

Until large-scale nuclear weapons testing was started in the early 1950's the potential problem of environmental contamination with radionuclides was not widely recognized (1). Initially, radionuclide contaminants originating from the fallout of weapons testing were generally regarded as insoluble and biologically unavailable. For example, early reports in the mid 1950's which suggested that radionuclides might reach man through milk (2,3) were received with some skepticism. However, many aspects of the entry of environmental contaminants into the biota, especially their flow into and through food chains have received considerable attention since that time.

Radionuclides often become dispersed and diluted upon release into the environment. The concentrations resulting from environmental "mixing" are usually very low and hence of little concern. However, radionuclides may accumulate in water, soils, or sediments and may also be "magnified" or concentrated in the tissues of living organisms. Nature can, therefore, receive an innocuous amount of radionuclide and in some circumstances, give it back to man in a potentially significant package (4). In fact, we now recognize that a major contribution of radiation exposure received by the world's population has come from radionuclide-contaminated food, mainly agricultural crops but also from aquatic organisms (1,3).

Many radionuclides are omitted in this discussion because of their extremely low abundance and occurrence. The radionuclides considered to be of importance in this study are listed under the following three headings which represent the source of the nuclides:

(i) Natural or primordial radionuclides:

uranium-238
thorium-234
thorium-230
radium-226

radon-222
lead-210
potassium-40
carbon-14

(ii) Weapons testing:

strontium-90
cesium-137
tritium

(iii) Reactors:

Major Importance	Lesser Importance
tritium	cerium-144
iodine-131	iron-59
strontium-89	barium-140
strontium-90	ruthenium-106
cesium-134	zirconium-95
cesium-137	krypton-85
cobalt-60	plutonium-239
	americium-241

Exposure Pathways

The aquatic, atmospheric and terrestrial environments are potential pathways of radionuclide exposure to man.

If plants and animals are to be of any significance in the passage of radioisotopes to man through food chains in the environment, they must accumulate the radionuclide, retain it and be eaten and digested by other organisms (5).

Radionuclides may be passed through several stages (trophic levels) of a food-web, and concentrations can either increase or decrease between trophic levels. This depends on the particular radionuclide and organism. Organisms differ in metabolism and as such have varying degrees of nuclide contamination and different retention times.

The concentration of a radioelement by an organism is usually discussed in terms of a concentration factor. This factor refers to the ratio of radionuclide levels in the organism to environment levels. In general, the concentration of radionuclides reaches higher levels in the lower plant and animal forms, such as bacteria, protozoa, and phytoplankton than in higher forms such as vertebrates and vascular plants (6).

The flow of the radionuclides, listed above, in the aquatic, atmospheric and terrestrial environments are discussed below.

4.1 Aquatic Environment

i) Introduction

A number of exposure pathways to man involving the aquatic transport of radionuclides can be postulated. For surface water ecsystems, the principle exposure pathways, generally in order of decreasing importance include (92):

Aqueous Discharge-Waterway-Drinking Water Supply-Man
Aqueous Discharge-Waterway-Seafood/Fish-Man
Aqueous Discharge-Waterway-Aquatic Plants-Animals-Man
Aqueous Discharge-Waterway-External Exposure
Aqueous Discharge-Waterway-Sediments-External Exposure

Other pathways could include the deposition of radionuclides from atmospheric and terrestrial sources to surface water bodies, and the migration of radionuclides via groundwater.

In general, these pathways can be divided into two major groupings: those involving direct population exposure (via external whole body exposure or via ingestion in drinking water), or those involving the food chain. In order to quantify exposure from direct pathways, the concentration of specific radionuclides in water at various points in the water body must be determined.

ii) Aquatic Transport Mechanisms

For surface water bodies, the dispersion of radionuclides depends on physical mixing, which in turn is a function of such factors as the depth of water, type of bottom, shoreline configuration, wind, the direction and speed of currents, the temperature, depth and initial mixing achieved when the discharge is introduced to the waterbody. Each surface water body has its own mixing characteristics. Problems in determining the mixing characteristics in the aquatic environment are further complicated by other physical and biological processes. For example, if a pollutant is introduced as a suspended solid it can settle to the bottom, be filtered by certain organisms, or become attached to plant surfaces. Pollutants in solution can be adsorbed on suspended organic and inorganic solids or can be assimilated by plants and animals (93).

Bottom sediments often act as a sink for pollution, but they may also become a source under certain conditions (93). The ability of suspended and bottom sediments to absorb and adsorb radionuclides from solution, thereby concentrating otherwise dilute ion species, may in some circumstances create a significant pathway to man (91).

Subsurface movement of radionuclides, through the soil to subsurface aquifers, and subsequent transport by groundwater tends to occur at a very slow rate (94).

iii) Aquatic Biological Mechanisms

Surface and groundwaters can acquire radioactivity from fallout, natural mineral deposits, liquid effluents from nuclear fuel cycle activities, and from the leaching and surface runoff from waste management areas associated with these fuel cycle activities. In addition to direct exposure pathways to man, dispersed radionuclides in water can enter the aquatic biological ecosystem. A very brief description of this ecosystem is abstracted from Eisenbud (93, Page 152) in the following four paragraphs:

> "In an aquatic ecosystem, the supply of basic compounds such as carbon dioxide and of elements such as oxygen, calcium, hydrogen, and nitrogen is contained either in solution or is held in reserve in the bottom sediments. These nutrients are absorbed and metabolized through the utilization of solar energy by two main types of food-producing organisms: rooted or large floating plants and minute floating plants called phytoplankton. Since food production by the higher plant forms is limited to relatively shallow water, it is the phytoplankton that have the main responsibility for converting the mineral resources of the aquatic environment into food for the higher organisms.
>
> The phytoplankton serve as food for the smaller zooplankton, which, in turn, serve as the basic nourishment of several higher trophic levels. The phytoplankton also serve as food for certain filter-feeding fish and bottom-dwelling animals. Sedimentation of the excrement of aquatic animals and the action of organisms which decompose dead plants and animals eventually complete the cycle by returning the nutrient elements to abiotic forms in which they again become available to the phytoplankton."

Aquatic organisms also sequester trace elements to varying degrees, and this phenomenon must be taken into consideration when any decision is made as to the rate at which any given radionuclide can be released to any body of water. In fresh water, where mineral constituents are usually present in very much lower concentrations than in sea water, the concentration factors (ratio of the concentration of an element in an organism to the concentration in the water) tend to be higher than in the oceans (93).

> "The sediments play a predominant role in aquatic radioecology by serving as a repository for radioactive substances which they pass by way of the bottom-feeding biota to the higher trophic levels. Pollution introduced into a body of water reaches the bottom sediment primarily by adsorption on suspended solids that later deposit on the bottom. The deposited remains of biota that have absorbed or adsorbed pollutants may also be an important source." (93, Page 157)

The physical, chemical and physiological behaviour of radioisotopes in the aquatic environment is essentially identical with that of the stable isotopes of the same element (5). Thus, if the behaviour of a particu-

lar element in an ecosystem is known, the attendant behaviour of the various radioisotopes of the same element can be predicted.

Members of the thorium and uranium series occur in natural waters (8,7). The principal long-lived nuclide of concern is radium-226 although thorium-232 and uranium-238 may also be present in measurable amounts (89). Potassium-40 and carbon-14 have also been measured in natural waters and their biota. Natural potassium contains 0.012% potassium-40 (9). In sea water, potassium-40 is the dominant source of radioactivity whereas it is a minor contributor in fresh water because of its low concentration (10).

Mawson et al. (11) reported that the effluents of a reactor with an open cycle cooling system contained strontium-89 and 90, cesium-137, cerium-144, ruthenium-106 and uranium-238. The nuclides zinc-65, lead-210, iodine-131, tritium, cobalt-60, zirconium-95, cerium-141 and 144 have also been observed in the aquatic environment (12, 13, 14, 15, 16, 17, 18, 19, 20). In brief, the principle liquid effluents of interest are tritium, iodine-131, cesium-137, cesium-134, strontium-90, strontium-89 and cobalt-60 (21). The most important atmospheric discharges (and hence potential fallout to surface water) from a CANDU reactor include iodine-131, strontium-89, strontium-90, cesium-137, cesium-134, cobalt-60 and tritium (21).

In this section, the literature on the uptake of several radionuclides into the aquatic food chain is introduced. The various radionuclides are segregated into two groups: natural and man-made sources.

Natural Radionuclides

The nuclides thorium-232 and uranium-238 appear to pose few problems as environmental contaminants. The concentration of uranium in natural waters is generally very low (22). Thorium is generally found in low concentrations in water as it is readily precipitated and is relatively immobile in biological systems (8,23). The bio-accumulation coefficients or concentration factor of uranium in living organisms show a gradual decrease in the food chain: algae - animal benthos - fish (25). Kovalsky et al., (25), observed that the least amount of uranium is accumulated by the organs and tissues of predatory fish such as trout as compared with vegetable-eating fish, like carp, which displayed the greatest amount. They surmised that differences in the accumulation of uranium by different fish species depends on their individual food chains. Uranium entering the fish accumulates mainly in the supporting and covering tissues, scales, bones, fins and skin. Uranium is incorporated into the elementary bone composition of fish mainly as ions replacing calcium in the bone apatite.

Radium-226 is a decay product of uranium-238 and may assume a position of importance where high concentrations occur (1). Fresh water usually contains less than 0.1 pCi/l radium-226 but levels up to 730 pCi/l have been reported (8). Water sediments and aquatic plants display elevated radium-226 content in streams contaminated with this isotope (26,1).

Lead-210 is a decay product of radon-222 which in turn is a decay product of radium-226. A certain fraction of the radon-222 escapes from solid matrices into the atmosphere where it decays to form lead-210 which can gradually return to the biota as natural fallout (27). Limited data are available on the movements of radioactive lead through the aquatic environment. Magno et al., (28) and Hill (29) have stated that water containing lead-210 makes an insignificant contribution to the total amount of background radiation exposure in the United States.

Man-Made Radionuclides

Ruthenium-106 can be found in reactor effluents. Irrigation may be an important process in the recycling of ruthenium-106 through the biota because of the nuclide's high water solubility. In furrow irrigation, plants could be contaminated by ruthenium-106 via the soil through sprinkle irrigation. There is the additional direct contamination from the wetting of foliage.

In marine ecosystems, algae are believed to be able to accumulate ruthenium-106 and growing populations of algae are believed capable of concentrating considerable amounts of ruthenium-106 from the environment (30,31). The movement of ruthenium-106 seems to be basically through the aquatic environment because of its high water solubility. The nuclide is accumulated by marine algae and probably by fresh water forms as well.

Cobalt-60 is a common radionuclide contaminant in nuclear reactor systems. Because of its long half-life, measurable amounts of the isotope can be found in receiving waters (32). Cobalt is an essential element for many organisms and as such is physiologically accumulated. For example, at least one marine animal and a number of fresh water plants and fish species have displayed high concentrations of the nuclide (32,33).

Nuclear weapons testing and reactor wastes have also released tritium into the aquatic environment. Tritium is one of the least toxic nuclides but its relatively long half-life of 12.3 y ensures that it will accumulate in the environment (1). Tritium closely follows the movement of hydrogen in biological systems; so, once released, it rapidly enters all living material. Tritium is not considered to be a serious problem when taken up by an animal because the biological half-life is short. For example, in cats, it was shown to be only 15-45 days (34).

Iodine-131 may present a hazard to man and the aquatic biota in the event of a release. The nuclide has a high fission yield, volatility, biological availability, rapid passage through biological systems, and concentrates in a small mass of tissue (1). According to Garner (1), iodine-131 (half-life of 8 days) is a good example of a group of short-lived radionuclides which are important only if they enter animal or man soon after their release to the biota. For the first few hours after a release inhalation will be the only exposure route of significance. After a period of time, however, and in areas further from the point of

release, ingestion will be a factor. In this general scheme, water is a minor contributor.

Fallout from weapons testing and reactor wastes include radioisotopes of strontium and cesium. Radioactive strontium and cesium when introduced into the aquatic environment are concentrated by plants and animals (35,36,37).

Strontium-90 can enter bodies of water directly by fallout or by runoff and erosion from areas contaminated with the radionuclide. The isotope is deposited in the sediments of streams and reservoirs (35,1,27). Strontium has the capacity to exchange for calcium and this, in effect, is the basis for the phenomenon of strontium-90 accumulation in plants and animals. The degree of accumulation is dependent upon the species of organism. Ophel and Fraser (32) have shown that certain plant types can discriminate between strontium-90 and calcium. Some species of marine seaweed discriminate strongly against calcium and concentrate strontium while, generally, biological organisms utilize strontium less effectively than calcium.

Fresh water fish accumulate strontium-90 partly from the ingestion of contaminated food but largely from direct absorption from the water (38,39). Lebedeva (40) has also shown that strontium-89, a radionuclide waste from reactors, is concentrated by fish in a similar fashion. Man may, therefore, be exposed to strontium-89 and 90 by consumption of contaminated fish and by ingestion of strontium-laden water.

Cesium-137, unlike most radioelements, is more concentrated in the higher levels of food chains. For example, ninefold increases of cesium-137 have been reported through the plant-mule/deer-cougar chain, fourfold increases have been reported in the lichen-caribou-wolf chain and a threefold increase in the concentration in humans compared with that in their food (37,42,43). Cesium-137 is rapidly concentrated by aquatic plants and animals. It appears that a balance is attained within two weeks (44,90,45).

Radioactive cesium introduced into a reservoir is rapidly taken up by bottom sediments. Aquatic plants growing on cesium-137 contaminated sediments accumulate the radionuclide. Wlodek (46) also observed that the amount of cesium-137 bound to plants and the stability with which it is bound varies.

Cesium-137 has a relatively long half-life in several fish species and thus is accumulated (47,36). Kolehmainen et al. (47) observed that an increase in cesium-137 concentration factors occurred in the fauna of relatively clear oligotrophic lakes. This was related to the reduced current of particulate matter in these lakes compared with eutrophic lakes.

The radionuclide zinc-65 has been observed in the aquatic environment. Zinc-65 is vertically transported through ocean depths primarily through the sinking of fecal pellets from fish in the upper waters (14). A similar mode of transport might exist in fresh water lakes although the

nuclide is likely more apt to be evenly distributed in much smaller volumes of water. Zinc is an essential element for many organisms and is, therefore, metabolically incorporated. Zinc-65 accumulates in the tissues of a gastropod which comprises a substantial portion of the sunfish's diet (48). Thus zinc-65 is transported through an aquatic food chain and may reach man through the consumption of zinc-65 laden fish. Zinc-65 is also concentrated in other aquatic animals as well as water plants (44,31). Concentration factors for zinc-65 in marine organisms are of the order of thousands of units, reaching tens of thousands for some molluscs (mussels and oysters), but for sponges, worms and a number of echinoderms they are only tens or even units. In comparison, the concentration factors for zinc-65 in fresh water organisms appear to be tens or hundreds of units. The concentration factors are also related to the concentration of calcium in the water. High levels of zinc-65 in food organisms in the aquatic environment may pose a potential threat to man.

4.2 Atmospheric and Terrestrial Environments

i) Introduction

The airborne transport of radioactivity can give rise to a number of pathways which ultimately affect man. A number of the more important pathways in general order of significance are listed below (92):

Atmospheric Discharge-Whole body external exposure
Atmospheric Discharge-Inhalation exposure
Atmospheric Discharge-Deposition on grass-Cattle-Milk-Man
Atmospheric Discharge-Deposition on leafy vegetables-Man
Atmospheric Discharge-Deposition on grass-Cattle-Beef-Man
Atmospheric Discharge-Deposition on soil-Plants-Man

Other food stuff-related transport mechanisms can be postulated, and the inter-relationship between the atmospheric discharge and the aquatic environment could be considered. Pathways in the atmospheric/ terrestrial environment are inter-related to aquatic pathways by three principal modes: Direct atmospheric deposition on surface waters, transport of ground-deposited radionuclides to surface waters via run-off, and the selective movement of certain radionuclides through soil and groundwater. However, the examples listed above likely represent the principal transport mechanisms for most situations.

In order to quantify these transport mechanisms, one must initially define the source characteristics and then through atmospheric dispersion modelling, estimate the suspended and deposited concentrations of the various radionuclides as a function of time and space. These aspects are briefly considered below.

ii) Atmospheric Transport

The dispersive power of the atmosphere directly affects the dilution of emissions released into it. The greater the dispersive power, the lower the contaminant concentrations downwind from a source. The important factors in dispersion include:

(a) wind speed
(b) turbulence, atmospheric stability
(c) mixing depth
(d) terrain effects
(e) local micrometeorlogical effects.

The wind speed acts directly to reduce concentration as the emission leaves the stack by providing separation between particles or gas molecules as they are released.

The turbulence of the wind acts to mix a pollutant with ambient air from the surroundings. As a plume moves downwind (at the speed of the mean wind) it expands at the edges through the action of small turbulent eddies that mix surrounding air into the plume. Much larger eddies move

the entire plume about in space. The combination of the foregoing eddy effects produces the expansion and meandering that is usually evident when the atmosphere is turbulent and thus unstable to some degree. When the atmosphere is stably stratified, large vertical motions are suppressed. The plume expands slowly in response to the low level of turbulence and small scale eddies. In such situations, atmospheric concentrations remain higher than for unstable, turbulent atmospheric conditions.

The foregoing discussion assumes that the plume spreads in an unrestrained way in both vertical and horizontal directions. This unlimited situation is not always encountered, rather transitions from stable to unstable or neutral stability may result in elevated surface concentrations for short periods of time. With transition to stable conditions aloft, trapping occurs and the plume then is restrained in its ability to disperse upward. The layer of air and, therefore, the amount of air available for dilution is reduced leading to higher concentrations than for unrestrained turbulent dispersion.

Irregular natural terrain can constrain, trap, or alter flow patterns producing higher concentrations than found for flat terrain. Micrometeorological behaviour at land and water boundaries can result in a trapping-type localized circulation known as sea-breeze or lake breeze.

In order to determine downwind groundlevel airborne concentrations of radionuclides from known or estimated source terms, conventional dispersion modelling techniques are used. Since these modelling techniques to determine airborne concentration as a function of space and time are well known (eg. see references 95, 96, 97, 98, 99, 100), they are not reviewed in the chapter. It should be noted, however, that the transport of airborne radionuclides is not inherently different from the transport of conventional pollutants except where radioactive decay must be considered. In general, this involves modifying the source term (Q) in the conventional dispersion equation to $Q\exp(-\lambda t)$ where λ is the decay constant of the radioisotope of interest (sec^{-1}) and t (sec) is the transit time from the stack to the position of interest (x). Alternatively, this can be expressed in terms of average wind speed $\bar{u}$ and downwind distance (x) as: $Q\exp(-\lambda x/\bar{u})$.

Predicted groundlevel airborne concentrations of specific radionuclides at specific spatial coordinates can be used directly to estimate radiation doses to individuals either from immersion in a radioactive plume or via the inhalation/transpiration modes. Similarly, these airborne concentrations can be used to estimate the quantity of the radionuclides deposited on the ground surface. The principal deposition mechanisms include:

- gravitational settling
- dry deposition (deposition via attachment of radionuclides on suspended dust particles by surface impaction, electrostatic attraction and chemical reaction) and
- precipitation scavenging (rainout, snowout, and washout)

Deposition of radionuclides on the ground potentially gives rise to whole body external exposure, and exposure via food pathways.

iii) Terrestrial Transport Mechanisms

As indicated in the previous section, the atmospheric/terrestrial pathway can lead to direct exposure to an individual by whole body external exposure from airborne radionuclides, from deposited radionuclides, and by inhalation exposure. Radionuclides deposited in the terrestrial environment also give rise to a number of indirect exposure pathways resulting from selective adsorption or deposition of these radionuclides on foliage and from the movement and reconcentration of certain elements through the food chain.

The terrestrial biota receive radionuclide contamination primarily through fallout and precipitation. These contaminants enter soils and are accumulated by terrestrial vegetation, which, when consumed directly by man or through man's ingestion of contaminated organisms may pose a potential hazard to the human population.

The aquatic pathways for radionuclide exposure to man have been discussed in section 4.2. As previously stated, these aquatic pathways may contribute radionuclides to the terrestrial environment through irrigation and foliage wetting.

Radionuclides present in the atmosphere are generally in particulate form. The amount of a radionuclide deposited on a particular plant is, obviously, related to the surface area of the plant and its structure since rough leaves will retain more fallout particles than smooth ones.

Soils may act as a sink in which an individual radionuclide may be stored. In the soil, there may only be a slight chance of the radionuclide entering the biota. However, the soil may also act as a reservoir from which plants and animals can be exposed to the radionuclide for long periods after the initial soil contamination (27). The above phenomena are dependent on the chemical behaviour of the radionuclides in the soils. Like radioisotopes in the aquatic environment, chemical behaviour in the terrestrial biota will be essentially identical with that of a radionuclide's stable isotopes.

In this section, the literature on the uptake of selected radionuclides into the terrestrial food chain is briefly discussed. Considering the complex ecological relationships between plants, animals and man, there is clearly a large number of pathways leading from trace concentrations of radionuclides in air to their appearance in the diet of man and animals. The relative importance of some of these relations will vary with geography and dietary habits.

Radionuclides selected for review are segregated into two groups:

Natural radionuclides:	uranium-238, radium-226, thorium-232, lead-210, potassium-40, tritium, and carbon-14

Man-made radionuclides: strontium-90, cesium-137, and iodine-131

Natural Radionuclides

The degree of uptake by plants of uranium-238, radium-226 and thorium-232 from the soil varies with plant species and radioelement content of the soil (49,50).

Uptake of uranium-238 by plants depends on several factors including plant species and the availability of uranium-238 in the soil. For example, uranium in a water-soluble quadravalent state (such as UO_2) can be carried away by leaching waters (51). Thorium-232 is strongly adsorbed on soil materials unlike uranium-238. Radium-226 levels are greater in more organic, and alkaline soils.

Uranium-238 has been observed in the tissues of pigs, poultry and in milk presumably as a result of the consumption of uranium-238 contaminated plants. Most of the uranium-238 ingested by animals is found in the bones, wool and skin (25). In one study (52) of all the animal products tested, milk had the smallest concentration of uranium-238. The major dietary sources of uranium-238 exposure to man in the United States were, as follows (in decreasing order of importance): potatoes, bakery products, whole grain products and meat. Fruit also comprised a significant source (22) while the uranium-238 in water was a negligible contributor. It should also be noted that other isotopes of uranium will likely act in a similar fashion to uranium-238.

Radium-226 is absorbed from soil and uptake by plants is highest from acid soils. Once in the plant tissue, it does not appear to be readily mobile (53). Radium-226 can reach man through the cow-milk-man chain and it is estimated that approximately 0.02% of the radium-226 in a cow's diet can be expected to be transferred to each litre of milk (54). Garner (1) indicates that no particular food element appears to predominate in the transfer of radium-226 to man although in most countries the major contribution came from eggs, root vegetables, fresh vegetables and fruit.

Thorium-232 is also accumulated by plants. The amount of thorium-232 in plant tissues is subject to considerable fluctuation but the pattern of distribution within a given plant parallels the patterns of uranium-238 and radium-226 (53). In order of amount of uptake, radium-226 is the greatest followed by uranium-238 and thorium-232. Thorium-232 may reach man through the consumption of contaminated plants and by the ingestion of animal tissues and animal products. The radioactive thorium-232 has accumulated in these animals through their consumption of thorium-232 contaminated plants.

Lead-210 is a decay product of radon-222. It is estimated that in the United States air contributes about 25% of the total lead-210 intake (29) while water makes a negligible contribution (28,29). Plants are considered to be the major source, and their contamination is primarily through aerial deposition (55).

As an example of a pathway to man, lichen is an efficient accumulator of lead-210 (56). This plant comprises a signficant portion of the diet of reindeer and elk. Most of the consumed lead-210 is deposited in the bone of the deer and elk and this, according to Kauranen and Mattienen (56) acts as a barrier against further transfer of lead-210 to man. Only very small amounts of lead-210 were found in tissues other than bone in the elk and reindeer reiterating that in this particular food chain, lichen-reindeer/elk-man, lead-210 poses a negligible threat to man.

Postassium-40, tritium, and carbon-14 are naturally occurring nuclides but tritium is also increasing in amount from the testing of nuclear weapons and from reactor operations.

Potassium-40 remains in fairly constant equilibrium with the stable isotopic form. Nevertheless, potassium-40 in man can constitute an important source of internal radiation. Potassium-40 enters plants but the rate of entry varies considerably with the type of soil, the species of plant and its stage of growth (23). Consequently, the quantities of potassium-40 ingested by man varies.

On the basis of absolute levels of radioactivity, potassium-40 might be a radionuclide to which close attention would have to be given. Russell (57), however, correctly points out that the potassium content of animal tissues is under close homeostatic control.

Tritium closely follows the movement of hydrogen in biological systems (1). It has been shown that tritium moves downward through the soil after winter rain and upwards in the summer as water is lost from the surface by evaporation and transpiration (34). In fact, loss of water to the biosphere by transpiration may actually increase surface and air levels of tritium. Tritium has been observed to be bound to organic plant matter, mainly in seeds which for example comprise a major dietary component to kangaroo rats residing in a nuclear test area (34). The half-life of tritium in these rats was between 15-45 days. Generally, tritium is not a major concern because of its relatively rapid biological decay. Bound tritium does however show a higher biological half-life. Tritium has also been observed in milk. Kirchman et al., (58) reported that tritium was transferred largely to the liquid phase of milk and that the total activity of the dry matter (lactose, casein and fat) was less than the liquid phase. This was interpreted as indicating that the fraction of tritium incorporated into organic molecules is secreted more slowly than that from the pool of body water.

Carbon is an element essential to all forms of life. Carbon-14 is a natural radionuclide formed from neutron activation of nitrogen. Small amounts are also present in reactor effluents (1). Carbon-14 which is present in the atmosphere as carbon dioxide (CO_2) is taken up by plants and incorporated into their tissues (59). These plants may then transfer carbon-14 to man when consumed. Carbon also occurs in soils, mainly in humus and carbonate minerals and the carbon-14 is added through incorporation of crop residues as fresh organic matter (27). Carbon-14 is transferred to animal tissues (including man) through the consumption

and ingestion of contaminated plants. The radionuclide is eventually excreted as CO_2 or as carbonate in urine and feces. Garner (1) indicates that plant and animal tissues rapidly equilibrate with carbon-14 in the atmosphere and that the activity in tissue can be considered to be the same as in air. Compared to its long radioactive half-life, its biological half-life is relatively short.

Man-Made Radionuclides

The radionuclides strontium-90, cesium-137 and iodine-131 have been observed in high concentrations in milk and milk products, meat, poultry and vegetable matter. All three nuclides originate from either weapons testing or in the effluents of nuclear reactors.

Milk assumes a position of great importance in the human diet as it provides calcium and is the major food and sometimes the sole food of infants. The dairy cow can ingest radioactive material that has deposited on or been incorporated into plant tissues. The nuclides are then rapidly transferred to milk which in turn is consumed by man soon after collection. Thus the grass-cow-milk chain is important in regards to the deposition of biologically available radionuclides of short half-lives (1). One such example is the incorporation of iodine-131 into milk. This nuclide has a half-life of 8.1 days.

Ruminant animals are likely to consume relatively significant quantities of radionuclides as they graze on plant material which contains radionuclides from both deposition and incorporation of the isotopes in plant tissues from soil. The meat of ruminant animals, needless to say, is a highly significant component of the human diet.

Poultry that are kept on free range may accumulate radionuclides in their tissues and eggs (60). The shell of the egg affords protection against strontium-90, cesium-137 and cerium-144, but iodine-131 can penetrate the egg (61). The shell apparently binds most radionuclides, making their passage to the egg impossible.

Strontium-90 is found in soils from the widespread general contamination from atmospheric fallout and in certain areas from acute localized contaminating events (62). The availability of strontium-90 to plants is determined mainly by the exchangeable calcium content of the soil. Strontium-90 is accumulated by various types of plants, including lichens and pasture grasses, as well as some vegetables (63,64,65). The amount of strontium-90 absorbed is dependent on the plant species and proportion of calcium and strontium-90 in plant tissue to their relative concentrations in the soil (66).

Strontium-90 has been found in milk and the activity in milk varies with soil conditions, the type of graze consumed and the type of farming (67). Milk appears to be the largest contributor of strontium-90 exposure to man and it has been estimated that 65% of dietary strontium-90 comes from this source (23).

As another example, the lichen-reindeer-man food chain can be a significant exposure pathway for strontium-90 to man. The bones of reindeer-breeders in the Soviet Union exhibit strontium-90 (64). The reason for higher levels of strontium-90 in this chain, and for cesium-137 as well, is a prolonged (tens of years) growth period of the first link, the lichen, which is the main source of radionuclides for the next two links. Strontium-90 is washed out of the lichens more rapidly than cesium-137 and this is evidenced by the lower levels of strontium-90 in the bones of reindeer and in the excretory wastes of reindeer-breeders while an increase in cesium-137 in both phases was observed (64). Thus, cesium-137 is more selectively accumulated than strontium-90 in this chain. The fact that strontium-90 accumulates principally in the bones of reindeer means that it is practically stopped from the further migration to the human body. The strontium-90 content in the edible organs forms about one-thousandth (per kg tissue) of its content in bones. Thus, man's consumption of meat from animals that have grazed on strontium-90 contaminated plants is not as great a contributor of radiation exposure as milk.

Cesium-137, unlike strontium-90 accumulates mainly in the soft edible tissues and most of all in muscles. For example, its radioactivity in reindeer muscles (per kg weight) is about a thousand times greater than strontium-90 activity (64). Thus, the amount of cesium-137 that can be ingested by man appears to be significant compared with strontium-90. The basis for cesium-137 accumulation in animal tissues is the presence of this nuclide in vegetable matter that is consumed.

In many soils cesium-137 is firmly bound to clay minerals, and, even in sandy soils cesium-137 appeared to become fixed about three years after contamination (69). The availability of cesium-137 to plants from contaminated soils, however, is small. In comparison with strontium-90, the rate of entry of cesium-137 is generally one-tenth to one-fiftieth that of the former nuclide (68,63). However, once incorporated into the tissues of plants or deposited via fallout, cesium-137 displays a greater mobility than strontium-90 and is less readily removed from plants by rain than strontium-90 (71). Thus, whereas the entry of cesium-137 into plants from soil is less than strontium-90, the consequences of direct contamination may be greater.

Body burdens of cesium-137 two to three times higher than for the rest of the United States have been reported in residents of Florida (72). This was related to higher levels of cesium-137 in the milk which resulted from the dairy cattles' ingestion of a type of grass in the area that accumulated cesium-137 at a relatively higher rate than other feed grasses (73). Various regions in the U.S.S.R. have also been identified where body burdens of cesium-137 were greater than average due to the contamination of milk (74).

Iodine-131 can present a hazard to man and animals because of its high biological availability and rapid passage through biological systems. Because of this radionuclide's relatively short half-life (8.1 days) it is important only if it enters animals or man shortly after its release (1). Iodine can be released from reactor fuel as elemental iodine.

Some of this is adsorbed on to particulates, although iodine-131 released in the air may remain as a gas several miles from the point of release (80). Most of the released iodine-131 deposits as particulate matter and, thus, iodine-131 exposure by inhalation is relatively insignificant compared with the ingestion route. It is now well recognized that man's main exposure to iodine-131 comes from the consumption of iodine-131 contaminated milk.

Iodine-131 in the gaseous state is readily incorporated into the plant tissue, presumably through small pore-like openings or stomata in the leaves, while iodine-131 on particles stays on the surface of the leaves (81). Both types of iodine-131 are consumed with the plants by the cow. A grazing cow covers approximately 4000-8000 m^2 in a day and, thus, she may ingest a relatively significant amount of iodine-131 (82). The chemical forms of the iodine-131 on the grass are such that iodine-131 can be readily taken up into the blood of the cow. In fact, Thompson (83) states that at least 70% of deposited iodine-131 should be available to the cow.

Iodine is an essential element for the maintenance of normal thyroid activity. Thus, the cow thyroid accumulates iodine-131 since about 0.5 - 0.8% of the daily iodine intake is directed toward this organ resulting in a fairly long biological half-life, while most of the ingested iodine-131 is excreted quite rapidly.

Bergstrom (81) estimates that between 0.04 and 0.20% of the total iodine uptake is secreted in the milk within 7 days after intake. The delay between collection and consumption for many foodstuffs is sufficient to allow radioactive decay to reduce iodine-131 to insignificant levels (1). Milk is one food item that is an exception as it is perishable and, therefore, consumed relatively fresh. Cheese may also be a contributor as the time taken to process milk into cheese may not be sufficient to allow radioactive decay to occur.

Iodine-131 may also reach man through consumption of contaminated vegetables. In some parts of the world, milk may not necessarily be a major source of food. In Japan, for example, spinach was observed to contribute far more fallout iodine-131 to the human diet than milk (84). In addition, fresh fruit and vegetables may also be a potentially important source to local populations in the U.S.A. (85).

Less data are available for the terrestrial pathways of exposure for the radionuclides zirconium-95, zinc-65, cobalt-60, barium-140, cerium-144 and ruthenium-106. Nevertheless, a majority of these nuclides have been observed in the tissues of plants. For example, zirconium-95, ruthenium-106, cerium-144 and barium-140 were found in plants after a weapons test (86). In this case the vegetation concentrated the radionuclides from soils contaminated with fallout via their root systems. These same radioisotopes as well as zinc-65, ruthenium-106 and cobalt-60 were found in the tissues of lichens, caribou and wolf (87). The presence of cobalt-60 in lichens is in contrast with the findings of Nishita et al. (88) who observed that, although cobalt-60 was in the soil, the radionuclide was not detected in a species of grass. These

observations may reflect the variability that can occur through differences in the chemical state of the element, the soil and plant metabolism.

The group of nuclides discussed above are obviously entering food chains in which man is a link. However, the extent of their entry and their potential hazards are not totally known at this time. At any rate, the fact that they are observed in the biota and may occupy portions of various food chains make them a potential source of exposure to man.

4.3 Summary

From the foregoing, we can postulate biological mechanisms whereby radionuclides deposited in the terrestrial environment are taken up into the food chain and ultimately affect man. A quantitative understanding of the food chain transport mechanism may be required if one wishes to predict the dose to man from a given deposition of a radionuclide in the environment, or a given concentration in foodstuffs (93).

> "In practice, depending on local dietary habits and the composition of plant effluents, only a few food chains will be of critical importance in a given locality or population group. The ICRP has suggested the use of the critical pathway approach to designate such food chains. In essence this procedure suggests that the complex pathways, by which discharged radioactivity may result in public radiation exposure, can in practice be reduced to one or two pathways that are overwhelmingly more important than all others. For any proposed release, this approach still requires a preliminary study to identify and evaluate these critical pathways, the critical radionuclides, critical materials and critical population group. An integral part of such a study is a habits survey that provides data on consumption rates of certain foodstuffs or the handling time of certain materials. Unless this is done with some judgement a great deal of meaningless and redundant data can be produced at appreciable computer cost." (93)

References - Biological Pathways

1. Garner, R.J. "Transfer of Radioactive Materials from the Terrestrial Environment to Animals and Man." CRC Press. The Chemical Rubber Company. 57 pp. 1972.

2. Chamberlain, A.C., J.F. Loutit, R.P. Martin and R.S. Russell. "The behaviour of I^{131}, Sr^{89} and Sr^{90} in certain agricultural food chains." In: "Proc. Int. Conf. Peaceful Uses of Atomic Energy," Geneva 13:360. 1956.

3. Loutit, J.F. and R.S. Russell. "The effects of atomc explosion upon animals." Vet. Rec. 67:1012. 1956.

4. Odum, E.P. "Fundamentals of Ecology." 3rd ed. W.B. Saunders Co. Philadelphia, London, Toronto. 1971.

5. U.S.E.P.A. "Water Quality Criteria." National Academy of Sciences, National Academy of Engineering. Washington, D.C. 594 pp. 1972

6. McKee, J.E. and H.W. Wolf. "Water Quality Criteria." The Resources Agency of California. Publication No. 3A. 548 pp. 1963.

7. Kornberg, H.A. and J.J. Davis. "Food chains in fresh water." In: "Radioactivity and Human Diet". R. Scott Russell (ed). Pergamon Press Ltd. 552 pp. 1966.

8. Klement, A.W., Jr. "Natural radionuclides in foods and source materials." In: "Radioactive Fallout, Soils, Plants, Food, Man". E.B. Fowler (ed.) Elsevier, Amsterdam. pp.113. 1965.

9. Ahrens, L.H. and R.D. Evans. "The radioactive decay constants of K^{40} as determined from the accumulation of Ca^{40} in ancient minerals." "Phys. Rev." 74:279. 1948.

10. Revelle, R., T.R. Folsom, E.D. Goldberg and J.D. Isaacs. "Nuclear science and oceanography." Proc. Internat. Conf. Peaceful Uses of Atomic Energy 13:371. 1956.

11. Mawson, C.W., A.E. Russell, I.L. Ophel, A.R. Jones, W.F. Merritt and P.J. Parsons. "Waste management and monitoring at Chalk River." Atomic Energy of Canada Ltd. Report AECL-987. 1959.

12. Davis, J.J., W.C. Hanson and D.G. Watson. "Some effects of environmental factors upon accumulation of world wide fallout in natural populations." In: "Radioecology". V. Schultz and A.W. Klement, Jr. (ed). Reinhold Publishing Co., New York. 1963.

13. Fowler, S.W., M. Heyrand, L.F. Small and G. Benayoun. "Flux of ^{141}Ce through a euphasid crustacean." "Mar. Biol." 21:317-325. 1973.

14. Pearcy, W.G., E.E. Krygier and N.H. Cutshall. "Biological transport of zinc-65 into the deep sea." "Limnol. and Oceanogr." 22(5):846-855. 1977.

15. Schell, W.R. "Concentrations, physico-chemical states and mean residence times of ^{210}Pb and ^{210}Po in marine and estuarine." "Geochimica Cosmochimica Acta" 41:1019-1031. 1977.

16. Wahlgren, M.A. and J.S. Marshall. "The behaviour of plutonium and other long-lived radionuclides in Lake Michigan. 1. Biological transport, seasonal cycling and residence times in the water column." Proc. Ser. International Atomic Energy Agency p.227. IAEA-STI/ PUB-406. Vienna, Austria. 1975.

17. Berg, A.R. and G.M. Weiss. "Transfer of zinc-65 from sediments to chironomid larvae and to a fresh water fish and the effect of cadmium on transfer." Proc. Ser. International Atomic Energy Agency. p.121. IAEA-STI/PUB-406. Vienna, Austria. 1975.

18. Honstead, J.F. "Mechanisms of transfer of radionuclides to man in the vicinity of a nuclear facility." In: Proceedings of Joint FAO/IAEA/WHO Seminar, Vienna. IAEA:381. 1969.

19. Holtzman, R.B. "Concentrations of the naturally occurring radionuclides ^{226}Ra, ^{210}Pb, and ^{210}Po in aquatic fauna." Proc. 2nd Nat. Symp. on Radioecology. USAEC Conference 670503:535-546. 1969.

20. Jenkins, C.E."Radionuclide distribution in Pacific salmon." "Health Physics" 17(3):507-512. 1969.

21. Wong, K.Y. "Basis for the derived limits for the release of radionuclides in gaseous and liquid effluents from Ontario Hydro's nuclear stations." H.P.D.-73-6. Toronto: Ontario Hydro, 1973.

22. Welford, G.A. and R. Baird. "Uranium levels in human diet and biological materials" "Health Physics" 13:1321. 1967.

23. Russell, R.S. and K.A. Smith. "Naturally occurring radioactive substances: the uranium and thorium series." In: "Radio-activity and Human Diet". Pergamon Press. pp.365-379. 1966.

24. International Atomic Energy Agency. "Manual on Radiological Safety in Uranium and Thorium Mines and Mills." Safety Series no. 43. Vienna:IAEA, 1976.

25. Kovalsky, V.V., I.E. Vorotnitskaya and V.S. Lekarev. "Biogeochemical food chains of uranium in aquatic and terraneous organisms." In: Proc. Int. Symp. 1966. 329-332. Stockholm. Pergamon Press, Oxford. 1967.

26. Tsivoglou, E.C., S.D. Shearer, Jr., J.D. Jones and D.A. Clark. "Estimating human radiation exposure on the Animac River." "J. Amer. Water Works Ass." 52:1271. 1960.

27. National Research Council. "Environmental transport and effects of radionuclides." pp.22-34. In: "The Effects on Populations of Exposure to Low Levels of Ionizing Radiation". National Research Council. 1972.

28. Magno, P.J., P.R. Groulx and J.C. Apidianakis. "Lead-210 in air and total diets in the United States during 1966." "Health Physics" 18:383. 1970.

29. Hill, C.R. "Routes of uptake of ^{210}Po into human tissues." In: "Proceedings of International Symposium". Stockholm, 1966. Pergamon Press, Oxford. 1967.

30. Boroughs, H., W.A. Chipman and T.R. Rice. "Laboratory experiments on the uptake, accumulation and loss of radionuclides by marine organisms." In: "The Effects of Atomic Radiation on Oceanography and Fisheries". National Academy of Sciences - National Research Council, Washington, D.C. Publ. 551. pp.80-87. 1957.

31. Polikarpov, G.G. "Radioecology of Aquatic Organisms. The Accumulation and Biological Effect of Radioactive Substances". Reinhold Book Division, N.Y. 314 pp. 1966.

32. Ophel, I.L. and C.D. Fraser. "The fate of cobalt-60 in a natural fresh water ecosystem." In: "Radionuclides in Ecosystems". Proc. 3rd National Symposium on Radioecology. May, 1971.

33. Gong, J.K., W.H. Shipman, H.V. Weiss and S.H. Cohn. "Uptake of fission products and neutron induced radionuclides by the clam." Proc. Soc. Epth. Biol. Med. Med. 95(3):451-454. 1957.

34. Koranda, J.J. and J.R. Martin. "Persistence of radionuclides at sites of nuclear detonations." In: "Biological Implications of the Nuclear Age". USAEC Symposium Series No. 16:159. 1969.

35. Ophel, I.L., C.D. Fraser and J.M. Judd. "Strontium concentration factors in biota and bottom sediments of a fresh water lake." In: "Proceedings of the International Symposium on Radioecology Applied to the Protection of Man and His Environment." Rome. 1971.

36. Hasanen, E.S. Kolehmainen and J.K. Miettinen. "Biological half-time of ^{137}Cs in these species of fresh water fish: perch, roach and rainbow trout." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm, pp.921-924. 1967.

37. Pendleton, R.D., R.D. Lloyd, C.W. Mays and B.W. Church. "Trophic level effect on the accumulation of cesium-137 in cougars feeding on mule deer." "Nature" 204:708. 1964.

38. Ichikawa, R. "Strontium-calcium discrimination in the rainbow trout." "Records of Oceanographic Works in Japan" 5(2):120-131. 1960.

39. Shiffman, R.H. "The uptake of strontium from diet and water by rainbow trout." "USAEC Document, HW-72107. 1961.

40. Lebedeva, G.D. "Main pathways of Sr-89 migration in organism of benthos-feeding fish in a fresh water reservoir." "Radio-biologiya" 2(1):62-71. 1962.

41. Ophel, I.L. "The fate of radiostrontium in a fresh water community." In: "Radioecology" V. Schultz and W. Klement, eds. Reinhold Publishing Company, New York. pp.213-216.

42. Hanson, W.C., D.G. Watson and R.W. Perkins. "Concentration and retention of fallout radionuclides in Alaskan Arctic ecosystems." In: "Radioecological Concentration Processes". Proceedings of International Symposium. Stockholm, 1966. pp.235-245. 1967.

43. Gustafson, P.F. and J.E. Miller. "The significance of Cs-137 in man and his diet." "Health Physics" 16:167. 1969.

44. Chipman, W.A. "Biological aspects of disposal of radioactive wastes in marine environments." In: "Disposal of Radioactive Wastes". Vol. II International Atomic Energy Agency, Vienna. pp.3-15 1960.

45. Bryan, G.W. "The accumulation of radioactive cesium in crabs." "J. Mar. Biol. Assoc. U.K." 41(3):551-575. 1961.

46. Wlodek, S. "The behaviour of ^{137}Cs in fresh water reservoirs, with particular reference to the reactions of plant communities to contamination." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm, 1966. pp.897-912. 1967.

47. Kolehmainen, S., E. Hasanen and J.K. Miettinen. "^{137}Cs in fish, plankton and plants in Finnish lakes during 1964-1965." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm, 1966. pp.913-919. 1967.

48. Pozzi, G. and M. Mertini. "The accumulation, distribution and loss of zinc (^{65}Zn) in the gastropod "Viviparus atu" (Cristofoni and Jan)." "Malacologia" 16(1):227-230. 1977.

49. Popova, O.N., R.P. Kodaneva and P.P. Vavilov. "Question of distribution in plants of radium taken up from the soil." "Fiziologiya Rasteniy Vol. II." No. 3. 1964.

50. Gruzdev, B.I. "Plant accumulation of uranium, radium and thorium and distribution of these elements in the soil-plant system in certain natural phytocenoses." Summary of the reports at the All-union Congress on the problem "Microelements and natural radioactivity of soils." Petrozavodik 1965.

51. Hansen, R.O., R.D. Vidal and P.R. Stout. "Radioisotopes in soils: Physical-chemical composition." In: "Radioisotopes in the Biosphere". Caldecott and Snyder (eds.) University of Minnesota. pp.23-37. 1960.

52. Prister, B.S. "Behaviour of uranium in the biologic chain." AEC-tr. 7128, 194. (UNSCEAR Doc. No. A/AC. 82/G/L-1298) (no date).

53. Verkhovskaja, I.N., P.P. Vavilov and V.I. Maslov. "The migration of natural radioactive elements under natural conditions and their distribution according to biotic and abiotic environmental components." In: Proceedings of International Symposium. Stockholm, 1966. Pergamon Press. 1967.

54. Sansom, B.F. "The transfer of plutonium-239 from the diet of a cow to its milk." Brit. Vet. J. 120:158. 1964.

55. Hill, C.R. "Lead-210 and polonium-210 in grass." "Nature" 187:211. 1960.

56. Kauranen, P. and J.K. Miettinen." ^{210}Po and ^{210}Pb in environmental samples in Finland." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.275-280.

57. Russell, R.S. "Uptake and accumulation of radioactive substances in terrestrial plants - the radiobiological aspect." In: "Radioecological Concentration Processes". Proceedings of an International Symposium held in Stockholm. 1966. pp.367-382. 1967.

58. Kirchman, R., A. Lafontaine, J. Van den Hoek and G. Koch. "Transfer and partition of tritium in the principal constituents of milk from cows given contaminated water." "C.R. Seances Soc. Biol." 163:1459. 1969.

59. Gibbs, M. "Radioisotopes in plants: Absorption and incorporation of carbon-14 in cell metabolism." In: "Radioisotopes in the Biosphere". Caldecott and Snyder (eds.). pp.97-109. University of Minnesota. 1960.

60. Miaz, F.R., P.L. Wright, T.M. Ferguson and D.L. Anderson. "Fission product metabolism in hens and transference to eggs." "Health Physics" 10:777. 1964.

61. Petrovic, B. "Contaminability of eggs by radionuclides in conditions of external radiocontamination." "Meded. LandbHoogesch. OpzoekStns. Gent." 30:1223. 1965.

62. Comar, C.L. and F.W. Lengeman. "General principles of the distribution and movement of artificial fallout through the biosphere to man." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1968. pp.1-18. 1967.

63. Krieger, A.L., B. Kahn and S. Cummings. "Deposition and uptake of ^{90}Sr and ^{137}Cs in an established pasture." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.59-72. 1967.

64. Neustrueva, M.A., P.V. Ramzaev, A.A. Moiseev, M.S. Ibatullin and L.A. Teplykh. "The nature of 137-Cs and 90-Sr transport over the lichen-reindeer-man food chain." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.209-216. 1967.

65. Van der Borght, O., R. Kirchman, S. Van Puymbroeck and E. Fagniart. ^{45}Ca, ^{85}Sr and ^{134}Cs absorption and translocation in isolated root systems of tomato plants." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.415-420. 1967.

66. Fredriksson, L. and Aa. Eriksson. "Plant uptake of fission products. I. Uptake of ^{90}Sr in pot experiments in relation to uptake under field conditions." "Lantbrukshogsk. Ann." 36:3. 1970.

67. Underdahl, B. 1967. "The influence of the soil and the way of farming on the ^{90}Sr concentration in milk." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.73-76. 1967.

68. Russell, R.S. "Radioisotopes and environmental circumstances: the passage of fission products through food chains." In: "Radioisotopes in the Biosphere". R.S. Caldecott and L.A. Snyder. eds. pp.269-292. 1960.

69. Squire, H.M. and L.T. Middleton. "Behaviour of ^{137}Cs in soils and pastures: a long-term experiment." "Radiat. Bot." 6:413. 1966.

70. Fredriksson, L., B. Eriksson, B. Ramuson, B. Gahne, K. Edvarson and K. Low. "Studies on soil-plant-animal relationships with respect to fission products." Proc. 2nd International Conf. on the Peaceful Uses of Atomic Energy. (United Nations). 18:449-470. 1958.

71. Middleton, L.J. "Radioisotopes in plants: Practical aspects of aerial contamination with strontium^{89} and cesium^{137}." In: "Radioisotopes in the Biosphere". Caldecott and Snyder (eds.). pp.86-96. 1960.

72. Roessler, G.S., B.G. Dunavant and C.E. Roessler. "Cesium-137 body burdens in Florida residents." "Health Physics" 16:673. 1969.

73. Porter, C.R., C.R. Phillips, M.W. Carter and B. Kahn. "The cause of relatively high cesium-137 in Tampa, Florida milk." In "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.95-101. 1967.

74. Marei, A.N., R.N. Barkhudarov, N.J. Novikova, E.V. Petukhova, V.K. Chumak, L.D. Dubova and V.M. Brigamina. "Effect of the natural factors on ^{137}Cs accumulation in the body of residents in some geographical regions." "Health Physics" 19:114. (Abstract). 1970.

75. Liden, K. and M. Gustafsson. "Relationships and seasonal variation of ^{137}Cs in lichen, reindeer and man in northern Sweden. 1961-1965." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.193-208. 1967.

76. U.S. Public Health Service. "Radionuclides in Alaska caribou and reindeer March-May." "Radiol. Health Data Rep." 9:764. 1968.

77. Eckert, J.A., J.S. Coogan, R.L. Mikkelsen and P.N. Lem. "^{137}Cs concentrations in Eskimos, Spring 1968." "Radiol. Health Data Rep." 11:219. 1970.

78. Hanson, W.C. "Radioecological concentration processes characterizing Arctic ecosystems." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966.

79. Dahl, A.H., F.W. Whicker and G.C. Farris. "Wild deer as a source of radionuclide intake by humans and as indicators of fallout hazards." "Health Phys." 12:1809. (Abstract) 1966.

80. Perkins, R.W. "Physical and chemical form of I-131 in fallout." In: "Biology of Radioiodine". Bustad, L.K. ed. Pergamon Press, Oxford. 1964.

81. Bergstrom, S.O.W. "Transport of fallout ^{131}I into milk." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.159-174. 1967.

82. Koranda, J.J. "Metabolism of ^{131}I by dairy cows during long-term daily administration of the radioisotope." "Health Physics" 10:55. 1964.

83. Thompson, S.E. "Effective half-life of fallout radionuclides on plants with special emphasis on iodine-131." UCRL-12388, University of California. Laurence Radiation Laboratory. 1965.

84. Garner, R.J. and R.S. Russell. "Isotopes of iodine." In: "Radioactivity and Human Diet". R.S. Russell ed. Pergamon Press. 1966.

85. Thompson, J.C., Jr. "Reconsideration of the ^{131}iodine contribution from fruits and vegetables." "Health Phys." 13:883. 1967.

86. Romney, E.M., A.J. Steen, R.A. Wood and W.A. Rhoads. "Concentration of radio-nuclides by plants grown on ejecta from the Sidan thermonuclear cratering detonation." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966 pp. 391-398.

87. Hanson, W.C., D.G. Watson and R.W. Perkins. "Concentration and retention of fallout radionuclides in Alaskan Arctic ecosystems." In: "Radioecological Concentration Processes". Proceedings of an International Symposium. Stockholm. 1966. pp.233-246. 1967.

88. Nishita, H., R.M. Hang and A.J. Steen. "Solubility and plant availability of radionuclides in reactor activated soils." "Health Phys." 12:615. 1966.

89. Gahr, W.L. "Uranium mill wastes." In: "Industrial Radioactive Waste Disposal." p.85. Hearings before the Special Subcommittee on Radiation of the Joint Committee on Atomic Energy, Congress of the United States, January 28, 29, 30 and February 2, 3. Volume I, U.S. Government Printing Office, Washington, D.C. 1959.

90. Polikarpov, G.G. "Ability of some Black Sea organisms to accumulate fission products." "Science" 133(3459): 1127-1128. 1961.

91. U.S. Nuclear Regulatory Commission, "Regulatory Guide 1.113," Revision 1, U.S. NRC, 1977.

92. U.S. Environmental Protection Agency, "Environmental Radioactivity Surveillance Guide", U.S. EPA, ORP, 1972.

93. Eisenbud, M. "Environmental Radioactivity" Second Edition, Academic Press, 1973.

94. Eichholz, G.G., "Environmental Aspects of Nuclear Power" Ann Arbor Science Publishers, Inc., 1976.

95. Slade, D.H. "Meteorology and Atomic Energy 1968." U.S. Atomic Energy Commission, Office of Information Services, 1968.

96. Reeves, M. et al "A Computer Code for Analyzing Routine Atmospheric Releases of Short-Lived Radioactive Nuclides." Oak Ridge National Laboratory, Health Physics Division 1972.

97. Strenge, D.L. et al "Review of Calculational Models and Computer Codes for Environmental Dose Assessment of Radioactive Releases" Battelle Pacific Northwest Laboratories, 1976.

98. Cowser, K.E. et al "Evaluation of the Potential Radiological Impact of Gaseous Effluents on Local Environments." Proceedings International Symposium, Radioecology Applied to the Protection of Man and His Environment, 1972.

99. Binford, F.T. et al "Estimation of Radiation Doses Following a Reactor Accident," Oak Ridge National Laboratory, 1968.

100. Hoffman, F.O. et al "Computer Codes for the Assessment of Radionuclides Released to the Environment," Nuclear Safety 18: 343, 1977.

Health Effects 5

Introduction

In contrast to the widely-held impression that little is known concerning the biological effects of ionizing radiation, it is safe to say that more is known about this subject than about the effects of any other toxic or carcinogenic chemical to which man is occupationally or environmentally exposed. The research on ionizing radiation dates back to the turn of the century and has been carried out in many nations. It has been particularly intensive since the early 1940's when the atomic bomb was developed. The literature is now quite voluminous. A number of comprehensive reports have appeared in recent years, notably:

ICRP, 1966, 1968, 1969 (1, 2, 3)
NAS BEIR Report, 1972 (4)
UNSCEAR, 1972 (5)
NCRP, 1975 (6)

Much of what follows has been condensed from these and other recent reports. Attention is also directed to a forthcoming report of the Science Council of Canada entitled An Overview of the Ionizing Radiation Hazard in Canada, and to a new UNSCEAR report entitled Sources and Effects of Ionizing Radiation: United Nations Scientific Committee on the Effects of Atomic Radiation, 1977 Report to the General Assembly, with Annexes.

Much of the public's fear of ionizing radiation stems from the fact that the subject is highly technical, requiring a considerable knowledge of physics, mathematics and statistics, and of human biology. Deficiencies in one or more of these disciplines can result in an incomplete understanding of the significance of particular pieces of research and in the drawing of faulty inferences or conclusions.

A second factor contributing to the public's apprehension results from the attempt by scientists to determine the risk to health associated with exposure to low levels and low doses of radiation. A great deal is known of the dose-response relationship at relatively high radiation doses. The difficulty of obtaining detectable responses at very low doses of radiation (e.g. 5 or 10 rads) depends on the size of the population and the number of years over which it is studied, as is illustrated by the following table, adapted from Buck, 1959 (7). (The roentgen units shown in the table are approximately equivalent to rads).

TABLE 5.1 (12)

Minimum Population Sizes Which Must Be Studied At Various Doses To Reveal A Detectable Increase in the Incidence of Leukaemia

Dose from Birth to Age 34 (R)	Minimum Man-Years at Ages 35 to 44
5	6,000,000
10	1,600,000
15	750,000
20	500,000
50	100,000
100	30,000
200	10,000

Since only a few studies have been carried out on human populations which have received such low doses of radiation, it has been necessary for the scientist to estimate the risk from low doses of radiation by extrapolation from dose-response curves obtained at higher dose levels. This introduces the problem of whether the extrapolation should be linear, i.e. whether the response is proportional to dose even down to very low levels, or whether a more complex mathematical model should be used. It also introduces the question of whether there is a no-effect threshold at some low dose. No answer to these questions can be given at the present time.

Any discussion of the health effects of ionizing radiation must consider:

1. whether the source of radiation is external to the body or whether the radiation results from radionuclides stored in the various body tissues.

2. whether the dose of radiation to the body or target organs was delivered in a single massive dose or over a few days (as resulted from the bombing of Hiroshima and Nagasaki), or whether it was delivered in small amounts over several months or years (as could occur from internally deposited radionuclides or, in the case of x-rays, if the dose were "fractionated").

3. whether the effects appear shortly after exposure (acute effects), or are delayed for months or years.

5.1 Mechanisms for Injury

As noted earlier in this report, ionizing radiations are injurious to living tissues because they deposit energy in the cells through which they pass, dislodging electrons and disrupting the chemical bonds which link atoms into molecules.

The charged particles generated by the absorption of x-rays or gamma rays in tissues are electrons which have a relatively low density of ionization along their tracks. Heavy ions such as alpha particles lose their energy quickly and produce a dense column of ionization as they penetrate cells. Because of this high rate of energy loss, their range in cells is short. A 5.3 MeV alpha particle emitted from plutonium has a range in water of 41 μm with an average density of about 3500 ion pairs/μm (8). Due to slowing of the alpha particle, the ion density increases by a factor of 2 toward the end of its range. Thus, compared with electrons, energy from alpha particles is deposited in cells and tissues in a highly concentrated manner.

For cells which are highly differentiated and which do not proliferate, such as nerve, muscle and secretory cells, death of the cell may be defined as the loss of a specific function, e.g. the inability of a nerve cell to conduct an impulse. To destroy function in such non-proliferating cells, a dose of some tens of thousands of rads is required (9).

For cells which are actively proliferating, such as the bone marrow stem cells which produce the red and white blood cells, cell death may be defined as a loss of their capacity for sustained proliferation. Thus, if cancer cells can be stopped from proliferating by administration of a dose of radiation, the tumour can be eradicated. With respect to proliferative capacity, the mean "lethal" dose is usually less than 200 rads (9). An alpha particle which traverses the nucleus of a cell deposits more than enough energy, by several orders of magnitude, to destroy the cell's reproductive capability (8). Traversal of an alpha particle through the cytoplasm surrounding the nucleus can damage the cell, but leave its reproductive capacity unimpaired.

The mechanism whereby radiation causes cells to lose their reproductive capability is not fully understood. There is no reasonable doubt that the sensitive target sites are in the cell nucleus, rather than in its cytoplasm. Hall, 1973 (9), discusses the evidence for regarding the chromosomes in the nucleus as the primary target for irradiation damage. Radiation injury to the cell membrane may also contribute.

The chromosomes are composed of large macromolecules of DNA (deoxyribonucleic acid) and protein. The DNA macromolecule is a helical strand having a backbone of sugar phosphate molecules, each with a nitrogenous base attached to it. Four nitrogenous bases are involved, namely thymine, adenine, cytosine and guanine. The combination of the sugar phosphate molecule with a nitrogenous base is called a nucleotide. There are four different nucleotides, depending upon the nitrogenous

base. The DNA macromolecule is thus a spiral chain composed of many hundreds of the four different nucleotide units.

Some hundreds of nucleotides, chained together in a specific sequence, form a gene. Thousands of genes in turn are linked together to form the DNA macromolecule which together with protein forms the chromosome. The position of each gene in the chromosome is known as its locus.

The specific sequence of nucleotides in each gene constitutes the genetic information which is passed on from one generation to the next. If the sequence is altered, as by addition or deletion of a single nucleotide, or by a change in the nitrogenous base in a nucleotide, there will be a change in the genetic information. This is called a mutation. Mutations, or changes in the genetic code, may also occur if a chromosome is broken or if parts of a chromosome are rearranged within the chromosome or are interchanged with another chromosome.

Mutations may result from unknown natural causes (spontaneous mutation) or they may be produced by a number of toxic chemical agents or physical agents. Even an increase in temperature can cause mutations. Raising the gonadal temperature 10°C doubles the mutation rate. Ionizing radiation is a particularly effective mutagenic agent.

While some chromosome breakages may repair themselves, others persist, giving rise to abnormal chromosomes which may be observed by microscopic examination. Alternatively, the number of chromosomes normally present may be altered. Chromosome aberrations may be divided into two categories: stable aberrations which can pass through repeated cell divisions, and unstable aberrations in which the chromosome does not divide equally between daughter cells, so that both cell lines eventually die (10).

The production of stable aberrations in the genes results in the formation of a new or mutant line of cells with heritable characteristics which are passed to succeeding generations of daughter cells. If the mutation affects the germ cells (the sperm or ova), some of the offspring will carry the mutant genes in all their cells. The mutation may be so deleterious that the embryo may die before birth, or if the pregnancy goes to term the offspring may be deformed. Congenital deformities resulting from mutations in the genes are hereditary (See Section 5.3 on Genetic Effects).

If the mutation affects the other cells of the body (somatic cells) the effects are not passed on to the offspring, and are therefore not hereditary. However, the daughter cells of such somatic mutations will carry the defective genes. The resultant effect will depend upon the type of cell, as well as the particular genes, affected. Thus severe mutation of the bone marrow cells could result in suppression of their normal function of producing red and white blood cells, with a consequent reduction of these cells in the blood (anaemia or leucopaenia). Or the mutation might render the stem cells of the bone marrow more capable of rapid growth and multiplication, resulting in leukaemia.

Similar interference with the genetic material of other somatic cells could theoretically start up uncontrolled cell division in cells that do not normally divide during adult life, or do so at a slow, controlled rate. The cells produced by such uncontrolled multiplication, displace, and may invade, surrounding tissues, the result being a cancer.

The biological effects of radiation depend not only on the amount absorbed, that is the dose, but also on the dose-rate, the time over which a dose is absorbed (rems per hour or rems per day). The biological effects of a given dose in general decrease as the dose-rate decreases. For example, 400 to 600 rads given to the whole body surface at one time would probably be fatal, but if spread over 30 or 40 years would probably have no effect on the somatic cells, since they are able to recover when the dose-rate is low. Radiation causes injury when the dose-rate is increased to a point where the recovery can no longer keep up with the injury, and permanent biological change results.

Not all cells are equally sensitive to ionizing radiation. The more rapidly proliferating cells tend to be more sensitive than those which are less actively reproducing. Also, tissues which are less specialized or less differentiated tend to be more sensitive to radiation. The following represents the order of decreasing radiosensitivity:

1. Lymphoid tissues
2. White blood cells
3. Cells lining the gastrointestinal tract
4. Cells of the reporductive organs
5. Skin
6. Blood vessels, cells lining body cavities
7. Liver and adrenal glands
8. Other tissues, including bone, muscles and nerves, in that order.

5.2 Somatic Effects

The somatic effects of ionizing radiation (i.e. those which affect the exposed individual rather than the offspring) may be conveniently described under two headings: (1) Acute, (2) Delayed.

5.2.1 Acute Effects

In addition to the size of the absorbed dose and dose-rate, the acute effects of external exposure to ionizing radiation depend on the area of the body exposed to the radiation. Shielding of even a small volume of tissue decreases the severity of an otherwise whole-body exposure.

Exposure to 25 rads or less of x ray, gamma or beta radiation produces no detectable acute somatic effects. Doses of 50 to 100 rads may cause changes in the white blood cells, but no disability. Glasstone (11) has summarized the clinical effects of acute exposure to external radiation in Table 5.2, which shows the principal organs affected, the predominant signs and symptoms, the course of the illness, and the likely outcome.

It will be seen that the effects on the blood-forming tissues predominate at levels of 100 to 1000 rems, with injury to the skin and loss of hair occurring following doses of more than 300 rems. With acute doses of 1000 rems or more, there are signs of gastrointestinal and central nervous system injury.

According to Eisenbud (12) there has been little experience of acute effects of internal radiation such as would result from the inhalation or ingestion of radionuclides. If highly radioactive substances of low solubility were inhaled or ingested, injury to the respiratory airways and the alveoli of the lungs, and to the mucous membrane lining the gastrointestinal tract would occur. It is known that atrophy of the thyroid gland can be produced by intake of massive doses of radioactive iodine (several thousand rems) as well as by large doses of external x-irradiation.

From the viewpoint of environmental exposure, aside from exposure which might result as the consequence of a major nuclear reactor accident or as the result of nuclear bomb testing or atomic warfare, the acute effects of ionizing radiation are of little practical importance since the dose levels resulting from normal uranium mining and milling practices and reactor operations are too low to produce acute effects. Delayed somatic effects, however, may result from long exposure to low levels of radiation, as well as following exposure to high dosages.

5.2.2 Delayed Effects

The delayed somatic effects resulting from exposure to high doses of radiation may become apparent within a few months of the exposure, such as changes in hair and skin pigmentation. Of greater significance are those effects which first become apparent some years after exposure. These include leukaemia, cancers of the lung and other organs, cataract formation, impairment of fertility, and a possible tendency to reduced life expectancy.

TABLE 5.2(11)

SUMMARY OF CLINICAL EFFECTS OF ACUTE IONIZING RADIATION DOSES

	Dose (rem)					
	0-100	100-200	200-600	600-1000	1000-5000	Over 5000
Incidence of vomiting	None	100 rem:5% 200 rem:50%	300 rem:100%	100%	100%	100%
Time of onset		3 h	2 h	1 h	30 m	30 m
Principal affected organs	None		Hematopoietic tissue		Gastrointestinal tract	Central nervous system
Character-istic signs	None	Moderate leukopenia	Severe leukopenia; purpura; hemorrhage; infection; epilation above 300 rem		Diarrhea; fever; disturbance of electrolyte balance	Convulsions; tremor; ataxia; lethargy
Critical period postexposure	-	-	4 to 6 weeks		5 to 14 days	1 to 48 h
Prognosis	Excellent	Excellent	Good	Guarded	Hopeless	Hopeless
Convalescent period	None	Several weeks	1 to 12 months	Long	-	-
Incidence of death	None	None	0 to 80% (variable)	80% to 100% (variable)	90 to 100%	90 to 100%
Death occurs within	-	-	2 months		2 weeks	2 days
Cause of death	-	-	Hemorrhage; infection		Circulatory collapse	Respiratory failure; brain edema

It should be emphasized that most of our present knowledge concerning the relationship between the development of delayed effects and exposure to ionizing radiation has resulted from observations on animal or human populations exposed to relatively high cumulative doses. The few exceptions to this statement are specifically noted in the following brief reviews dealing with leukaemia and lung cancer.

(i) Carcinogenesis

The evidence available at the present time indicates that most important delayed effect of radiation on the mortality of human populations results from carcinogenesis, including the induction of leukaemia.

In reviewing and comparing the findings of various studies, a certain amount of difficulty was encountered in understanding precisely what was meant by the use of certain terms, particularly those referring to the risk of cancer from given doses of radiation. For example, it was not always immediately clear whether the risk (usually referred to in terms of 1,000,000 persons per rad or per rem) represented the total number of cases accumulated over a certain period of years, e.g.: 20 years, or whether it represented the average annual number of cases, or whether it represented a life-time risk, i.e., the total number of cases which were estimated to occur over a life-time in a million persons exposed, say, to 1 rad or rem. Two specific terms relating to risk require definition.

(a) Absolute risk. Under the linear dose model, the absolute risk may be expressed as the number of excess cases of cancer per unit of time in an exposed population of given size, e.g.: 1 case/10^6 exposed persons/year/rad.

(b) Relative risk is the ratio between the risk in the irradiated population and the risk in the non-irradiated population. It is usually stated as a multiple of the natural risk. The doubling dose, i.e. the dose that will double the normal risk, is a special example of a calculation of relative risk (4). The relative risk would be equivalent to

$$\frac{\text{observed number of cases}}{\text{expected number of cases}} \quad \text{or} \quad \frac{O}{E}$$

It should be noted that in some studies the relative risk is calculated as

$$\frac{\text{excess cases (due to radiation)}}{\text{expected cases}} \quad \text{or} \quad \frac{O-E}{E}$$

In many cancers induced by environmental agents (whether chemical or physical such as ionizing radiation) the exact time or date of exposure is known. It is characteristic of such cancers in humans that a latent period of some years elapses before the first cancers are observed. The incidence of cancers then increases during the following years until a peak is reached, then decreases toward normal.

Lundin et al, 1971 (13) have shown that the occurrence of lung cancers in their group of uranium miners could be predicted using a log-normal distribution with a median latent period of 10 years from the date of first exposure. (Some 70% of their miners smoked cigarettes, and it is possible that this concurrent exposure to tobacco smoke may have acted to reduce the median latent period).

Bizzozero et al, 1966 (14) have found that the occurrence of leukaemia following a single brief exposure to radiation also followed a log-normal distribution. The use of the log-normal in assessing the dose-response relationship between radiation and cancer in populations which have sustained their exposure at low dose rates over a number of years provides a logical method for giving less weight to the doses incurred in the last few years prior to the development of the cancer, and greater weight to the doses incurred earlier in employment, i.e. more than 5 to 10 years prior to the cancer occurrence. An appropriate weighting of the doses received, in order to establish the "effective dose", is particularly important in assessing the radiation-cancer risk in population groups which have received their exposure over many years.

Leukaemia

An increased frequency of leukaemia, as compared with its normal incidence, has been reported among Japanese survivors of the atomic bombings at Hiroshima and Nagasaki (15), among children irradiated in infancy for enlargement of the thymus gland, among patients whose spines were irradiated for ankylosing spondylitis, among radiologists and among children irradiated in utero during the mother's pregnancy (16, 17).

The Japanese atom bomb survivors showed a peak incidence of leukaemia in 1951-1952, some 6 years after exposure. The incidence rate in 1951 was about 11 times higher than that in the unexposed population. Though the rate for the survivors has declined markedly since 1952, it has not returned to normal even 25 years after exposure. The dosages received by the Japanese survivors is estimated to have been in the range of 100 to 900 rads, giving an increased incidence of leukaemia proportional to dose at a rate of about 20 cases per million exposed people per rad over a 15- to 20-year follow-up period. This incidence of radiogenic cases could be compared with a normal frequency of about 1,200 cases in a population of one million unexposed persons over the same follow-up period and based on an average incidence of about 6 cases per hundred thousand per year (12).

The incidence of leukaemia in patients receiving x-ray therapy for ankylosing spondylitis was slightly lower than that for the Japanese bomb survivors.

The increase in leukaemia in children irradiated in utero reported by Stewart and Kneale, and by MacMahon, is of particular interest since the x ray dose received by the fetus was only of the order of 1 rem. Mole, 1975 (18) has assessed these reports and considers the evidence for an increased risk of leukaemia and of childhood cancers at this dose level is sound. On the other hand, no increase in leukaemia or childhood

cancers has been found in Japanese children who were irradiated in utero at the time of the atom bombing. Some of these children were estimated to have received 250 rem prenatally.

A similar negative finding was reported by Saenger et al, 1968 (19) in hyperthyroid patients who received 8.9 mCi of iodine-131 (a whole-body dose of about 20 rem), compared with non-irradiated hyperthyroid controls. However, the hyperthyroid population as a whole had a leukaemia incidence about 50% higher than that in the general population, suggesting that hyperthyroidism itself may be associated with an increased risk of leukaemia.

The BEIR report (4) considers the radiogenic risk of leukaemia to be about 1 case/10^6 exposed persons/year/rem, and that susceptibility to induction of leukaemia is several times higher in those irradiated in utero or in childhood, as well as in those irradiated late in adult life, than in individuals of intermediate ages.

(Note: See also subsection on Cancer and Preconception Radiation.)

Breast Cancer

An increased incidence of breast cancer has been reported in female tuberculosis patients subjected to repeated x ray fluoroscopy, in women given localized x ray treatments for acute mastitis, and in Japanese women who survived the atom bomb (15). A carcinogenic effect of radiation on breast tissue has also been demonstrated in laboratory animals. The BEIR report states that for cancer of the female breast the observed mortality at high doses is approximately 3 deaths/10^6 exposed women/year/rem. The report edited by Okada et al suggests that the absolute risk of breast cancer is about 2.1 cases/10^6 persons/year/rad.

Thyroid Cancer

At high dose levels and high dose rates, tumours (both malignant and non-malignant) of the thyroid gland show an increase in incidence proportional to increasing dose in exposed populations. Children appear to be several times more susceptible to the induction of thyroid tumours than are adults. Thus, an increased incidence in thyroid cancer was found in children whose thyroids received more than 200 rads of x-ray for treatment of enlarged thymus glands (20), whereas no excess of cancers was observed in adults similarly treated (21). An increased incidence of thyroid cancers was also reported in Japanese A-bomb survivors who were under 20 years of age at the time of exposure. The increase was greater in women than in men.

More recently, Modan et al, 1974 (55) reported 12 thyroid cancers in some 10,902 children who received low dose x-radiation for tinea capitis. The follow-up period was 13 years; the x-rays were administered from 1 to 12 years before the start of the follow-up. Only 2 cancers of the thyroid developed in an equal number of control children. The average dose of x-rays to the thyroid was 6.5 rads, giving a risk estimate for low doses of x-radiation of 10.9 cancers per 1 million per year

per rad. This value is about the same, or slightly higher, than the estimate provided in the BEIR report for high dose x-ray or gamma radiation (see below).

The carcinogenic risk associated with exposure to radioactive iodine is of particular interest because of its selective concentration in the thyroid gland and because the dose to the thyroid when fresh fission products are released to the atmosphere (as could happen after a nuclear reactor accident) may be the limiting factor in determining the length of time an individual may remain in the area of fallout.

An increased incidence of thyroid abnormalities was found in a group of Marshall Islanders some 15 years after they were irradiated by fallout from a thermonuclear explosion in 1954. The thyroid doses from radioactive iodine were estimated to range from 160 to 1,400 rem, superimposed on a whole-body irradiation of about 175 rem. In this instance, the shorter-lived radioiodine isotopes, which are 10 to 20 times more biologically effective than iodine-131, were responsible for much of the tissue damage.

In rats, it has been found that the carcinogenic effectiveness of iodine-131 is about one-tenth that of x-rays. Whether this applies in humans, particularly children, is not known.

The BEIR report estimates the risk of thyroid cancer from radiation to be 2.5 to 9.3 cases (not deaths)/10^6 exposed children/year/rem to the thyroid, averaged over the 5th to 25th years after exposure.

Lung Cancer

It is now well known that an increase in lung cancer in humans can result from the inhalation of cigarette smoke and a variety of air contaminants such as asbestos, mustard gas, hematite, and compounds of chromium, nickel and arsenic, as well as a variety of organic chemical compounds. Concurrent exposure to one or more of these agents may play a role in the increased incidence of lung cancer reported in uranium miners in Czechoslovakia and south-eastern Germany (22, 23), the Colorado plateau (13) and in Ontario (24, 25, 26), as well as in fluorspar miners in Newfoundland (27) and in non-uranium metal miners in Sweden (28).

In each of the foregoing mining populations, as well as in the British hematite miners, there was occupational exposure to increased levels of radon and radon daughters (100 pCi/ litre of air, or higher). Radon daughters appear to be highly carcinogenic in association with cigarette smoking.

An increased incidence of lung cancer has also been reported in Japanese survivors of the atom bomb (15) who were exposed mainly to external gamma and neutron radiation. A significant excess of lung cancer has also been reported in patients with ankylosing spondylitis treated with x-rays at doses to the bronchial epithelium of about 400 rads (29).

Most of the lung cancers associated with exposure to air contaminants, including radon daughters, arise in the epithelium lining the bronchi. Very few develop in the deeper spaces of the lung (the alveoli). Considerable effort has been made to estimate the dose of radiation delivered to the bronchial epithelium in the uranium mining population. When radon gas is in equilibrium with its daughters, approximately 90% to 95% of the dose is from the radon daughters (30). Removal of the radon from the mine atmosphere also eliminates the build-up of radon daughters. In still air, approximately 3 hours is required for radon and radon daughters to reach equilibrium. In a mine with several air changes per hour, equilibrium will not be reached and the level of the radioactivity in the air will consequently be reduced to some fraction of that present at equilibrium. Thus, with one air change per hour the disequilibrium factor (defined in Chapter 1) is about 0.7. With two air changes per hour the ratio is about 0.4 (31).

Radiation levels in uranium mines are customarily measured in Working Levels (WL), defined in Chapter 1, and the dose received by the miners in Working Level Months (WLM), (i.e. 170 hours of exposure to 1 WL). In certain studies (e.g. the uranium miners in Czechoslovakia) exposure was measured in picocuries of radon per litre of air. Conversion of this unit to WL requires a knowledge of the state of equilibrium between radon and its daughters existing in the mine.

Calculation of the dose delivered to the bronchial epithelium (or to the lung, taken as a whole organ) requires a knowledge, or at least certain assumptions, concerning a long list of factors, including:

1. The degree of dustiness (including oil and water droplets) of the mine air.

2. Particle size distribution and density of the dust in relation to its respirability.

3. The proportion of radon daughters adsorbed on respirable dust particles and nuclei (usually quite high).

4. The volume of air breathed daily (the product of frequency and depth of respiration).

5. The fraction of the dust (or radon daughters) retained in the lung. This will depend on (a) the deposition characteristics of dust of various sizes and densities in various parts of the respiratory tract, and (b) the residence time of the particles at the various sites of deposition. This in turn depends on the solubility of the dust particles and on physiological clearance mechanisms in the lung such as the muco-ciliary action of the cells lining the trachea, bronchi and bronchioles, and the phagocytic removal of dust particles to the upper respiratory tract (where they will be spat out or swallowed) or to the lymphatic system (where the dust will tend to collect in the lymph nodes).

6. The energy dissipated by the radon daughters (most of this is in the form of alpha particle radiation) and the volume of tissue cells irradiated.

7. The relative biological effectiveness (or quality factor) of the alpha or other radiation. In various studies the RBE or QF_1 values used for alpha radiation varied from less than 10 to a factor of 20.

8. The contribution made by other radionuclides (e.g. thoron and its daughters).

9. Assumptions regarding the effects of non-uniformity in dose distribution through the various parts of the lung.

Depending upon the estimates or assumptions used for each of the above factors, as well as others, the calculated dose, in rems, for a 1 WLM exposure can vary by at least two orders of magnitude. The BEIR report estimated 1 WLM equal to 5 rems to the bronchial epithelium.

To the uncertainties inherent in the above calculations the realization should be added that it is important, as mentioned previously, to incorporate some rational method of weighting the dose received in past years to arrive at an estimate of the effective dose, i.e. the dose which actually contributed to the development of the lung cancer.

With only one or two exceptions, in all of the studies in which an increased incidence of lung cancer with increasing radiation dose has been reported, the excess of cancers occurred in men (usually smokers) who had accumulated in the range of 120 WLM (estimated 600 rems) of exposure, or more. The BEIR report, after reviewing the studies published to 1971, estimated the risk of lung cancer from radiation exposure to be approximately 1 death/10^6 exposed workmen/year/rem.

Attention is drawn to one recent report which attempts to relate cancer incidence to low levels of external radiation (32). This study uses proportionate mortality to compare the frequency of deaths, from cancers, of various sites in exposed and non-exposed workers at the Hanford plant in the state of Washington. The exposed workers were defined as those having one or more positive film badges (0.01 rads of exposure) during their service at the plant. The average life-time dose accumulated by those dying of cancers was 2.10 rads, and that for men dying of other causes was 1.62 rads. The average life-time dose accumulated by the exposed workers was 1.72 rads, and that for non-exposed workers was apparently less than 0.01 rad. The findings in this study are not reported here, since the study is open to criticism on several counts. First, the dosimetry involved is suspect; background radiation is approximately 0.1 rad per year, i.e. ten times greater than the minimum recorded total exposure for a life-time of work for a member of the exposed group. Second, from the epidemiological and statistical point of view proportionate mortality is not a sufficiently powerful method to distinguish real differences in the exposure experience of the cancer and non-cancer groups at low levels of mortality. Third, an independent

preliminary analysis of the mortality experience of the Hanford workers using a cohort approach, which is intrinsically more sound than the proportionate mortality method, has failed to substantiate many of the conclusions reached by Mancuso et al (33). At the present time, the quantitative relationships between cancers and radiation dose derived in the report by Mancuso et al must be regarded as unproven.

Although lung tumours are readily induced in animals by radiation exposure (4), it is worth noting that as yet there has been no success in producing cancers by the inhalation of radon and radon daughters alone, even at very high dose levels. Lung cancers have been produced in rats, however, when they were first exposed to uranium dust or to nonradioactive cerium hydroxide in the form of a single inhalation exposure, followed by repeated exposures to high levels of radon (34). It would appear of some interest to determine whether exposure to a certain level of airborne dust is a necessary concomitant of radon exposure in the induction of lung cancer.

The experimental studies up to 1969 relating lung cancer to ionizing radiation from radionuclides administered to animals are reviewed by Bair, 1970 (35) and Sanders et al, 1970 (36).

Bone Cancer (Osteosarcoma)

A few bone cancers have been reported in persons receiving x-ray therapy in doses ranging from 3,000 to 15,000 rads for ankylosing spondylitis (29). Benign tumours of bone and cartilage have also occurred following much smaller doses of x-rays, usually less than 500 roentgens measured in air (4). No mention is made of bone cancer occurring in the Japanese A-bomb survivors in the report of Okada et al (15).

The major causes of radiogenic bone cancer have been (a) the ingestion of radium-226 and radium-228 (mesothorium) by luminous dial painters about the time of the first World War and in the years prior to 1926 (37), and (b) the intravenous administration of radium-224 (thorium X) for treatment of tuberculosis and ankylosing spondylitis (38).

Other sources of radium intake were the drinking of radioactive water nostrums, the oral or intravenous administration of radium solutions by physicians treating a wide variety of diseases during the 1920's, and ingestion of radium by chemists working in refineries and laboratories. Among some 770 dial painters, 51 cases of bone sarcoma and 21 cases of cancer of the head (mastoid redion) and nasal sinuses had developed to 1972. Among 900 patients receiving intravenous radium-224, 53 cases of bone sarcoma, but no cancers of the head or sinuses, had developed to 1970 (4).

In evaluating the dose-response relationships for radioactive isotopes which are concentrated in the body or body organs, it is necessary to include a consideration of their radiotoxicity. As stated previously, radium isotopes, as well as a number of other radionuclides including strontium and plutonium, behave chemically like calcium and are deposited in the bone.

When radium-226 is ingested, most of it passes through the intestinal tract unabsorbed. Depending upon the solubility of the radium salt, from 10% to 30% is absorbed into the blood stream. (The ICRP assumes the higher figure in its calculations, probably because the main source for ingestion is radium dissolved in water). In the blood the chemical properties of radium (and strontium) are such that they undergo cationic exchange with the replaceable calcium in bone. Initially the radium concentrates on the bone surfaces and in areas of active bone growth and replacement. It then gradually migrates throughout the entire bone mineral, though the distribution is uneven. The critical body organ for radium is thus the bone.

The biological half-life for excretion of radium-226 from the body is 900 days. Excretion of radium-226 from bone follows a power function with an ultimate value of 10 to 12 years. Because the range of penetration for alpha particles from radium-226 and its daughters is only about 25 to 50 μm in bone or tissue, the radiation dose is confined to the bone or tissue cells which lie directly in contact with the bone, such as the periosteum and endosteum and the epithelial lining of the nasal sinuses and mastoids. Very high radiation doses, in addition to initiating malignancies, can cause rarefaction and necorosis of the bones, leading to spontaneous fractures.

A residual skeletal burden of 1 μCi of radium-226 will, over 40 years, result in an average dose to the skeleton of 3,220 cumulative rads and a skeletal average dose rate of 56 rads per year (37).

Among the more than 650 radium-226 and radium-228 cases studied at the Massachusetts Institute of Technology up to 1970, no cases of bone sarcoma or other signs of radiation injury were detected in persons with a residual skeletal burden of less than 0.5 μCi of radium-226 (or radium-equivalent in the case of radium-228), some 35 years after exposure. If the residual radium burden some 35 years after acquisition was about 1 μCi or greater, then some individuals did have signs and symptoms which appeared clearly attributable to chronic radiation of their bones. With residual burdens of between 0.5 and 1 μCi there were a few instances of symptoms of injury (39).

Stating the response in terms of radiation dosage, Evans says, in his 1974 paper (37) "In more than 500 individuals with skeletal average doses below 1,000 cumulative rads, no signs or symptoms of clinically significant radiogenic effects have been observed thus far in the subjects studied at M.I.T." In the same paper Evans also noted that there is suggestive evidence that the time till appearance of the tumour increases as the dose decreases, and he states "If the trend to increasing appearance time with decreasing dosage is real, then there would remain a small dosage for which the required tumour appearance time exceeds the maximum life span", i.e. a practical threshold dose.

This finding has been reported in experiments in which beagle dogs were exposed to several alpha-emitting radionuclides, including radium-226, radium-228 and plutonium-239 (40). Rowland et al, 1970 (41) have summarized the dose-response data for the 770 exposed individuals studied

at M.I.T. and the Argonne National Laboratory. They found that an equation of the type $I = KD^2 e^{D/D'}$ gave the best fit for observed cases versus dose, where I = cancer incidence, D = mean cumulative bone dose and K and D' are constants. The exponential term allows for an apparent fall in incidence in the highest dose range. At lower values of D, an equation of this type reduces to a proportionality between incidence and the square of the cumulative dose. In effect, this particular relationship implies a very small probability of radiation-induced bone cancer at low cumulative doses, with a sharply rising frequency in the higher ranges, and results in a better fit to the observed incidence rates in this group than does a strictly linear fit to the data.

In the group of cases reported by Speiss and Mays, 1970 (38) who were given radium-224, the lowest cumulative dose at which bone sarcoma occurred was 90 rads. An attempt to explain the difference in dose response between the radium-226 cases and the radium-224 cases has been made by Speiss and Mays on the basis of the dose to the cells on the bone surface rather than average skeletal dose. According to their calculations, the dose to the surface cells from radium-224 is 9 times higher than the average skeletal dose, whereas with radium-226 the surface cell dose is less than the average skeletal dose by a factor of 0.63. On the basis of dose to the bone surface cells, the lowest dose at which bone cancer has been observed in men is approximately the same for the two isotopes, namly 810 rads for radium-224 and 570 rads for radium-226, suggesting that a threshold could exist for radium isotopes. The evidence for a threshold, however, is not conclusive since the populations at risk in the lower dose range are small.

The experimental evidence as to the carcinogenic effects of a number of bone-seeking radionuclides has been summarized by Mays and Lloyd, 1969 (42), 1972a (43) and 1972b (44). These authors concluded that for alpha emitters bone cancers increased linearly with dose in some studies, but showed a sigmoid dose-response relationship in others. For beta emitters the relationship also appears to be sigmoidal, i.e. the response at low doses was less than would be predicted by a linear dose-response model.

Recognizing the uncertainties in the relationship between dose and bone cancer induction at low dose levels, the BEIR 1972 (4) report concludes that at high doses, mortality from cancer of the skeleton approximate 2 deaths/10^6 exposed persons/year/rem.

Skin Cancer

While it is generally recognized that skin cancer can develop in persons who have received intensive irradiation of the skin, particularly in those who have developed radiodermatitis, there appear to be few data on which a doseresponse relationship can be evaluated. Human observations and experimental evidence suggest that no increase in skin cancers occurs below the 450 to 1,000 rad range. In mice, tumour induction has been reported to be proportional to the square of the dose (45).

Other Cancers

According to the BEIR, 1972 (4) report, excess incidences of lymphoma, cancers of the pharynx, stomach, gall-bladder, liver, nasal and mastoid sinuses, and tumours of the salivary glands have occurred following exposure to ionizing radiation. The evidence for an increased cancer risk for these sites is, at present, limited and in most instances is insufficient to warrant any conclusions regarding dose-response relationships. However, in their study of 10,902 children irradiated for tinea capitis, in addition to the increase in thyroid cancer previously mentioned, Modan et al, 1974 (55) found a significant increase in malignant and benign tumours of the brain and of the parotid gland. The x-radiation dose to the brain was about 140 rads. The BEIR report does state that for cancer of the gastro-intestinal tract, including stomach, the mortality at high dose levels approximates 1 death/10^6 exposed persons/year/rem, and that cancers of other sites may contribute a further 1 death/10^6 persons/year/rem.

Cancers Following in Utero Irradiation

In addition to the increased incidence of leukaemia reported in children whose mothers have received x-radiation to the abdomen during pregnancy, Stewart and her colleagues, 1958 (46) and 1970 (16), and MacMahon, 1962 (17) reported an increase in the incidence of cancers of solid tissues in children, occurring from shortly after birth to about the age of 8 or 10. In the MacMahon study, the increase in leukaemia was about 40%, and of other cancers was about 50% greater than normal. Mole, 1974 (47), analysing more recently published data by Stewart et al, also found that the excess of leukaemias and of solid cancers in singleton births and in dizygotic twins who had been irradiated in utero was about 50% greater than normal. Stewart and Kneale, 1970 (16) described a linear relationship between x-ray dose and the excess of cancers and estimated that there would be between 300 and 800 extra deaths before age 10 in 1 million children exposed to 1 rad of radiation shortly before birth.

No definite increase in childhood cancers was found in 1250 Japanese children exposed in utero to less than 500 rads at the time of the atomic bombings (48). Mole, 1974 (47), however, has reviewed later reports by Jablon and Kato and has found that, with a linear hypothesis, the overall induction rate of malignant disease between 0 and 10 years of age was 20 per million per rad for the A-bomb survivors exposed in utero. This figure may be compared with an overall risk of 240 malignancies per million per rad for antenatal radiography provided by UNSCEAR, 1972 (5).

Cancer and Preconception Irradiation

A series of at least 6 reports, based upon the "Tri-state study" conducted in Baltimore, Minneapolis and New York state (excluding New York city) has appeared since 1966 claiming a 60% increase in leukaemia in children whose mothers reported diagnostic x-ray exposures up to 10 or more years before conception, and a 30% increase (of borderline statis-

tical significance) in children whose fathers were irradiated prior to conception of the child (49, 50, 51, 52). Such an effect, if real, would have to be heritable, i.e. a genetic effect.

It has not been possible within the time constraints of this project to evaluate the evidence substantiating the findings in the Tri-state study. The BEIR, 1972 (4) report points out that a study, involving 6 indicators of genetic damage of the first generation following the Japanese atom bombings, has shown no detectable effects of radiation exposure, nor has any excess of leukaemia been found in this generation even though the radiation doses received by the parents prior to conception were much larger than those in the Tri-state study. The BEIR report states that "in the interpretation of those studies which have been reported an association between leukaemia and preconceptual irradiation remains uncertain".

Total Cancers

Among the Japanese survivors of the atomic bombings, the excess mortality from all forms of cancer, including leukaemia, over 20 years of follow-up corresponds roughly to from 50 to 78 deaths per million exposed persons per rem (4). In persons who received high doses of x-radiation for ankylosing spondylitis, the excess cancer mortality corresponds to a cumulative total of roughly 92 to 165 deaths per million persons per rem during the first 27 years after irradiation.

Newcombe, 1976 (53) has summarized the data from the BEIR, 1972 (4) report, the UNSCEAR, 1972 (5) report and from Pochin, 1976 (54) to table estimates of the cumulative risk of cancer induction during the 25-year (approximately) period following whole body irradiation (Table 5.3).

The values for favoured estimates shown at the bottom of the table allows for additional cases which may still occur with longer followup periods. Newcombe notes that "the figure shown for lung cancers is of little use for predicting the risks of lung cancer arising from localized exposures to radon gas and its daughter products, as in uranium mining, because of difficulties in calculating doses to the tissues involved".

(ii) Effects on Blood Cells

In addition to its leukaemogenic effect, exposure to ionizing radiation can affect those cells in the body responsible for the formation of the red blood cells (erythrocytes), the white blood cells (lymphocytes and granulocytes) and the blood platelets (thrombocytes) which are concerned with blood clotting.

Irradiation of the lymphoid tissues of the body may suppress the ability of precursor cells to form lymphocytes, resulting in a decrease in the number of circulating lymphocytes (lymphopenia). It may also induce changes in the chromosomes within the lymphocytes. The yield of chromosome aberrations is dose dependent. A recent paper by Lloyd and Dolphin, 1977 (10) indicates that chromosome analysis can be used to

provide an estimate of dose where no physical dosimeter was worn, and is frequently of value in resolving anomalous or disputed data from routine film badges.

Stimulation of lymphocyte formation, resulting in an increase in circulating lymphocytes (lympocytosis) has occasionally been reported in persons exposed to ionizing radiation, but appears to be of less significance.

Irradiation of the bone marrow by x-ray or gamma radiation or by radionuclides, by depressing the function of various precursor cells, may produce decreases in the circulating red blood cells (anaemia), the white cell granulocytes (granulocytopenia) or the platelets (thrombocytopenia). Radioactive phosphorus-32, a beta emitter, is used clinically in the treatment of polycythaemia vera, which is characterized by an over-production of red blood cells.

(iii) Radiation Dermatitis

As well as causing acute burns of the skin, exposure to ionizing radiation may cause delayed effects taking several weeks to develop. Healing is slow, and results in atrophy, increased pigmentation and a tendency to recurrent ulceration. Plastic surgical repair is frequently necessary.

Chronic overexposure of the skin to ionizing radiation also leads to atrophic changes and hyperkeratosis, as well as malignant changes.

(iv) Cataract Formation

For introduction of cataract affecting the lens of the eye, there is radiobiological and clinical evidence of a non-linear relationship between response and dose of radiation, this effect depending, presumably, on the killing of the cells in the lens (4). For x-rays and gamma rays, the threshold for cataract formation is between 200 and 500 rads when delivered in a single brief exposure, or about 1,000 rads when delivered over a period of months. For neutron radiation there is suggestive evidence of a threshold of around 75 to 100 rads, which would be equivalent to some 375 to 1,000 rems if neutrons are assumed to have a relative biological effectiveness of 5 to 10 times that of x-rays or gamma rays.

(v) Impairment of Fertility

The ovary develops a finite number of germ cells, or oocytes, early in life and lacks the ability to regenerate them. Destruction of the oocytes by irradiation or other means results in a permanent reduction of the ability to produce ova, or a reduction in fertility. In women, a minimum of 300 to 400 rems must usually be given in a single exposure to ensure sterility, and a dose of 1,000 to 2,000 rems is required if the dose is fractionated over a period of 10 to 14 days. Follow-up studies of the Japanese female survivors of the atom bombings has failed to disclose any lasting impairment of fertility (4).

TABLE 5.3

RISK ESTIMATES FOR THE INDUCTION OF CANCER
BY WHOLE BODY IRRADIATION *

(Adapted from UNSCEAR 1972, p 9, BEIR 1972, p 89,
and POCHIN 1976, p 33-34.)

Kind of Cancer	Cases per 10^6 man-rem
OBSERVED	
Leukaemia	15 - 40
Lung	10 - 40
Breast	6 - 20
Other	40
Thyroid (non fatal)	(40)
Total fatal	71 - 140
Non fatal	(40)
FAVOURED ESTIMATE	
Total fatal	150
Non fatal (including skin cancer)	(100)

* After Newcombe, 1976 (53).

Unlike the ovary, the tests has considerable capacity for regeneration of its sperm-producing cells, the spermatagonia. The latter are quite radio-sensitive. A single dose of 50 millirem is sufficient to result in temporary cessation of sperm formation. However, the surviving spermatagonia eventually regenerate the seminiferous epithlium and restore spermatogenesis. Restoration of normal sperm counts in men has followed within one to three years after doses ranging from 0.1 rem to near-lethal exposure. Fractionated exposure of dogs to 3 rems per week has resulted in sterility after a few months, whereas 0.6 rems per week for lifetime exposure produced no change in sperm count (4).

There is thus evidence, for both males and females that impairment of fertility is nonlinear with dose, i.e. that a practical threshold does exist for this effect.

(vi) Life-Shortening Effect

The possible life-shortening effect of ionizing radiation is discussed fairly fully in the BEIR, 1972 (4) report. There is conclusive evidence that sublethal doses of whole body radiation, whether administered as single or fractionated exposures, shorten life expectancy in rats, mice, dogs and other animals and that the life-shortening effect appears to be proportional to dose. Extrapolation of these results to man would predict a reduction of life expectancy of from 1 to 5 days per roentgen.

Most of the data pertaining to man have been derived from studies of person occupationally exposed while giving radiotherapy and of survivors of the Japanese atom bombings. The effects of a large number of variables, other than radiation dose, known to affect life expectancy such as age, pre-existing disease, concomitant exposure to other occupational contaminants, and socio-economic status renders the interpretation of such studies difficult. Increased mortality from causes other than cancer and leukaemia has been reported in several carefully controlled studies such as that by Seltser and Sartwell, 1965 (56) on American radiologists. On the other hand, studies of other occupationally exposed groups, such as dentists and x-ray technicians, and of the Japanese A-bomb survivors have failed to show a generalized increase in mortality or evidence of accelerated aging.

An increased mortality was found for infants exposed in utero during the Japanese atom bombings. The effect appears only in those exposed in the last trimester of pregnancy. Whether the effect was somatic or genetic is not known. A more recent report by Blot (15) found that radiation of the fetus in early pregnancy, even at doses as low as 10 to 20 rads, may result in reduced growth, smaller head size and mental retardation.

5.3 Genetic Effects

Any discussion of the genetic effects requires at least an elementary knowledge of genetics and the Mendelian laws of inheritance. Scientific progress in the field of genetics has been revolutionary in the past 20 years. A comprehensive consideration of the genetic effects of radiation is beyond the expertise of this contributor, and beyond the scope of this project. In the following brief discussion, no more is attempted that to present a basic understanding of the subject, and to indicate the major conclusions resulting from a number of specific studies and from more detailed assessments made by experts in the field. Reference is made, in particular, to:

ICRP Publication No. 6, 1969 (1)
NAS BEIR Report, 1972 (4)
UNSCEAR, 1972 (5)

The essential characteristics of any animal species are passed from one generation to the next by the chromosomes in the nuclei of the germ cells. In humans, somatic cells normally contain 46 chromosomes, half of which are derived from the father and half from the mother. Since somatic cells contain two matching sets (each of 23 chromosomes) they are said to be diploid. Germ cells (the ova and spermatazoa) each contain 1 set of 23 chromosomes and are therefore haploid.

Each somatic cell contains 2 sex chromosomes, an X and a Y chromosome in the case of males and 2 X chromosomes in females. During germ cell formation, when the chromosome count is halved, each ovum will receive an X chromosome from the mother, but a spermatazoon may receive either an X or a Y chromosome from the father. During conception, the combination of a Y chromosome from the sperm with an X chromosome from the ovum will produce a zygote with an XY combination, resulting in a male. Combination of an X chromosome from the sperm with an X chromosome from the ovum produces an XX zygote or female. The 22 pairs of chromosomes which are not sex chromosomes are known as autosomal chromosomes.

Occasionally a zygote may receive an extra chromosome (i.e. 47 chromosomes in the case of humans) resulting in a condition known as trisomy. Or a zygote may receive one too few chromosomes, a condition known as monosomy. Monosomies and trisomies appear to be a major cause of spontaneous abortion of early embryos. In addition, trisomies have been found to cause certain hereditary diseases such as Down's syndrome (monogolism). The trisomic XXY combination is responsible for Klinefelter's syndrome. On the other hand, Turner's syndrome has been found to be due to a monosomy with a single X chromosome present but no Y chromosome.

When a number of chromosomes in a cell is any number other than a multiple of the haploid number (i.e. occurs in monosomy and trisomy), the condition is known as aneuploidy.

Chromosome imbalance may also result from chromosome breakages. In the process of re-attachment of the pieces, there may be rearrangement of

the chromosomes. This causes no immediate abnormality, but leads to an increased frequency of unbalanced chromosome combinations in the next generation, frequently associated with physical deformities and mental retardation. Furthermore, the re-arranged chromosomes are heritable, so that the tendency to produce abnormal children is passed to succeeding generations.

The information which is transmitted by the genes within the chromosome we shall call a trait. In the simplest forms of inheritance only one site on the chromosome carries the gene which produces the trait. However, in all cells except the germ cells the chromosomes occur in pairs, and there are thus two genes for each trait. If both chromosomes of a pair contain the same gene (e.g. BB), the organism is said to be homozygous with respect to that trait, and will manifest the trait. If the two genes for a particular trait differ (e.g. Bb) the organism is heterozygous. In such instances the organism will manifest the trait of only one of the two genes, and that gene is said to be dominant. The other is referred to as recessive. A recessive trait will only become manifest when two gametes, each carrying the recessive gene (b) unite to give a zygote with a (bb) combination. If two heterozygous individuals reproduce, one offspring will be homozygous (BB), two will be heterozygous (Bb), and one will be homozygous (bb). The first three, carrying the dominant (B) gene will all manifest the dominant trait; the fourth offspring, carrying the (bb) combination will manifest the recessive trait.

Linkage is the term used to designate the association of two traits located on the same chromosome and therefore transmitted together. When the second trait is located on the X or Y chromosome it is said to be sex-linked. The X chromosome is much larger than the Y chromosome and may carry genes, either dominant or recessive, which are not represented on the Y chromosome. The combination of a recessive (x) chromosome with a Y chromosome results in a heterozygous (xY) male zygote which will manifest the recessive (x) trait. A female carrying the (xX) combination will not show the recessive trait. A well-known example of this kind of sex-linked recessive inheritance is haemophilia, in which the trait for defective coagulation of the blood is transmitted to half the male offspring (xY zygotes). The other half of the male children will have the (XY) combination and will not manifest the trait nor transmit it.

A dominant mutation manifests itself in the first generation and in each succeeding generation, regardless of sex. McKusick, 1971 (57) lists 415 diseases or abnormalities which are believed to result from dominant mutations, and another 528 for which the evidence is less well established. Examples of dominant inherited diseases are polydactyly (extra fingers and toes) and achondroplasia (short-limbed dwarfism). Recessive mutations, which require that the mutant gene be present in duplicate in order to manifest the trait, may not be expressed for many generations, until two heterozygous individuals carrying the same mutant gene meet and reproduce. McKusick lists 385 recessive hereditary diseases, plus 418 in which the evidence is less certain. Among the

recessive diseases transmitted by autosomal chromosomes are sickle cell anaemia, cystic fibrosis and Tay-Sach's disease. As mentioned, haemophilia results from a recessive mutation located on the X chromosome. X-lined recessive mutations are nearly always expressed only in males.

Before considering the dose-response relationships between ionizing radiation and genetic effects, it is convenient at this point to mention the possible mutational effects resulting from the transmutation of those radioisotopes that are incorporated into the DNA molecule. These isotopes are tritium-3 which transmutes to helium, carbon-14 which transmutes to nitrogen, and phosphorus-32 which transmutes to sulphur.

All three isotopes are beta emitters. The BEIR, 1972 (4) report has assessed the evidence available to 1971 and concluded that, while transmutation of these isotopes can result in DNA strand breakage and in some cases definite mutations, the effect of the beta radiations far outweighs any contribution from transmutation effects.

Most of our knowledge concerning the dose-response relationships between ionizing radiation and genetic effects come from studies of fruit flies (Drosophila) and mice followed over many generations. Comparable information is, of course, not available for humans. The mouse experiments are therefore of particular relevance.

A number of parameters have been used as possible indicators of genetic damage in human populations:

1. Sex ratio at birth (i.e. male/female birth ratio)
2. Frequency of stillbirths
3. Frequency of infant deaths
4. Frequency of abnormalities
5. Birthweights
6. Anthropometric measurements

The effect of radiation on sex ratio is explained as follows. If the mothers receive irradiation, X-linked lethal mutations will be expressed only in males, resulting in a decrease in male births and a decrease in the sex ratio. If the fathers receive irradiation, dominant X-linked lethal mutations will be expressed in the daughters, resulting in a relative decrease in female births and an increased sex ratio.

From studies of human populations, such as the Japanese who were exposed during the atomic bombings (15) and persons living in regions of high natural radioactivity such as on the monazite sands in Brazil (58), there is no direct evidence of genetic effects, even at high doses. Similarly, animal experiments in which mice were exposed to high doses of radiations (200 rems per generation) for as many as 45 generations have failed to show any effect in the offspring as measured by mortality, lifetime survival, fertility, growth, or other abnormalities attributable to radiation (59).

TABLE 5.4

Estimated effects of radiation for specific genetic damage. The range of estimates is based on doubling doses of 20 and 200 rem. The values given are the expected numbers per million live births.

	Current incidence per million live births	Number that are new mutants	Effect of 5 rem per generation	
			First generation	Equilibrium
Autosomal dominant traits	10,000	2,000	50-500	250-2,500
X-chromosome-linked traits	400	65	0-15	10-100
Recessive traits	1,500	?	very few	very slow increase

FROM: NAS-BEIR, 1972 (4)

However, such studies are believed to reveal only part of the total genetic damage. Thus, increased mutation rates have been produced in mice in which the spermatagonia and mature oocytes were irradiated. These studies showed that the mutational effects of irradiation at low dose levels, or protracted over time, are much less than those from high-level, brief exposures. With chronic irradiation exposures the frequency of gene mutations in mature mouse oocytes was only about one-twentieth that occurring after acute radiation exposure. Irradiated male mice which received 0.8 roentgens per minute to the spermatagonia had one-fourth to one-third the number of mutations that mice receiving 90 roentgens per minute had. There was no further reduction in the mutation rate when the dose rate was decreased to 0.009 roentgens per minute, nor any further increase when the dose rate was increased to 1,000 roentgens per minute. This dose rate effect is thought to reflect repair mechanisms within the cell, but which are overwhelmed at high dose rates. It also suggests that a practical threshold may exist for genetic effects.

Review of the animal studies indicates that the evidence for a dose-response relationship for genetic effects is so overwhelming that it must be assumed that humans are affected in much the same way.

After reviewing all the human and animal evidence available to 1971, the BEIR, 1972 (4) report concluded that the doubling dose of ionizing radiation (i.e. the dose of radiation which would produce mutations at a rate equal to that for spontaneous mutations in a population) was in the range of 20 to 200 rems per exposed person. From this it is assumed that a 1% increase in the mutation rate will be produced by exposure to 0.5 to 5 rems. Table 5.4, from the BEIR report, shows the estimated effects of radiation for specific types of genetic damage.

In Table 5.5, Newcombe, 1976 (73) shows risk estimates for the induction of hereditiary diseases by irradiation of the germ cells, together with an indication of the degree of uncertainty associated with each estimate. Newcombe also notes that revised estimates of genetic risks should appear in the forthcoming UNSCEAR report of 1977, and that it is expected that they will be somewhat less than those shown in Table 5.5.

5.4 Epidemiological Studies

The foregoing section on Health Effects, particularly Section 5.3 dealing with Delayed Effects, contains reference to much of the epidemiological literature on the effects of exposure of humans to high doses of ionizing radiation, as well as reference to a smaller number of studies (16, 17, 32, 46, 49, 50, 51, 52, 55, 58) in which the exposure was to low doses and/or low dose rates. Most of the studies, whether of high dose or low dose effects, concerned exposure received either occupationally or in the process of diagnostic radiology or radiotherapy. No attempt has been made to review all epidemiological studies of the effects of low dose and low dose rate exposure or to evaluate their findings. There are a number of other reports in the literature, e.g. lung cancer in British hematite miners (60) and the study of Frigerio et al, 1973 (61) on the carcinogenic hazard from low-level, low-rate radiation, to mention only two. A comprehensive review of the literature in this field, with careful evaluation of the findings, whether positive or negative, would in our opinion assist in the formulation of policy respecting the control of occupational and environmental sources of exposure.

With respect to the establishment of and participation in, future epidemiological surveys, it should be borne in mind that:

i) research on the harmful effects, both somatic and genetic, of low doses and low dose rates of ionizing radiation is urgently needed;

ii) the interval from first exposure to the development of effects is long, of the order of a decade or more, and the cumulative effects may not be fully apparent for many decades in the case of somatic injury, or for at least five or more generations in the case of recessive genetic mutations;

iii) the lower the level of response to be measured the larger must be the size of the population studies (see Table 5.1);

iv) the response must be related to accurate measurements or estimates of the cumulative exposure, thus requiring a considerable expenditure of time and effort in environmental sampling;

v) as far as it is possible to do so, the design of the survey must attempt to control for other variables which are known or suspected to affect the magnitude or type of the response, e.g. age, cigarette smoking, concomitant exposure to other chemical or physical agents, socio-economic status, racial or genetic susceptibility, etc.;

vi) the co-operation of other agencies or facilities will be needed, e.g. Statistics Canada or company insurance carriers for records of mortality for long-term follow-up studies, or chemical and laboratory facilities for the examination of exposed persons;

TABLE 5.5

RISK ESTIMATION FOR THE INDUCTION OF HEREDITARY DISEASES
BY IRRADIATION OF GERM CELLS

(Adapted from UNSCEAR 1972, p 7, BEIR 1972, p 57, and POCHIN, 1976, p 34)

Kind of hereditary disease	Natural incidence per 100 liveborn	Cases per 10^6 man rem	Uncertainty	Notes
Dominant	1	100	($\overset{\times}{\div}$ 3)	1
Chromosomal and recessive	1	-		2
Congenital malformations	2.5	200	($\overset{\times}{\div}$ 10)	3
Constitutional and degenerative	1.5			
Total	6	300	($\overset{\times}{\div}$ 5)	4

FROM: NEWCOMBE, 1976 (53)

1) Assuming 1 rem causes a 1 percent increase in the mutation rate of man, as it does in the mutation rate of the mouse, this figure would be 100. The uncertainty arises partly in extrapolating from mouse to man, and partly because the natural incidence of serious dominant disease in man has not been accurately measured. About 1/5 of the cases arising over all time due to exposure of a single generation (i.e. 1/5 of the number tabulated) would appear in the first post-irradiation generation.

2) Little, if any, increase in these diseases would be expected.

3) No increase in these diseases has been observed in laboratory mammals as a result of irradiation, and it is not at all clear that any would be expected, hence the high degree of uncertainty. If an increase did occur, exceedingly few of the total additional cases would appear in any single post-irradiation generation.

4) Although the confidence limits on the total of 300 cases per million man rem are wide, it is more likely that the true number is less than 300 rather than more.

vii) such studies are expensive.

This is not to discourage such studies, but to emphasize the care required in their planning, and the effort and expense involved if meaningful results are to be obtained.

5.5 Radiotoxicity of Selected Radionuclides

Chemical toxicity may be defined as the ability of a chemical compound to produce injury or exert an adverse effect on a biological system when it reaches a vulnerable or susceptible site in or on the body. The major factor that determines the degree of harmfulness of the compound is the dose of that compound. For compounds taken into the body over a period of time, the dose is the product of the rate of intake and the duration of intake, or time. The rate of intake of the compound is, in turn, the product of the concentration of the compound in the medium entering the body (air, water, food, etc.) and the amount of the medium taken in a specified period.

The result of intake of a chemical is a graded response which is related to progressive changes in dose. Of fundamental importance in assessing chemical toxicity is a knowledge of the relationships which exist between the dose of the chemical and the response that is obtained.

Radiotoxicity has been defined as the ability of the nuclide to produce injury, by virtue of its emitted radiations, when incorporated into the body. All of the statements in the preceding two paragraphs concerning chemical toxicity apply as well to radiotoxicity. The two forms of toxicity differ primarily in the nature of the body's response following incorporation in the body.

There are other similarities in the toxicological features governing the two forms of toxicity. The body does not distinguish between radioactive and stable isotopes; the biochemical reactions, physiology and metabolism are the same for both. Absorption of a compound from the gastro-intestinal or respiratory tracts, its concentration in the blood, its selective concentration in various organs, the metabolic pathways and detoxification mechanisms and its excretion via the liver or kidneys are not intrinsically different for radioactive or stable isotopes. Radiotoxicity differs from chemical toxicity in that, in addition to their inherent chemical toxicity, radioactive compounds produce injurious or adverse effects by their emitted radiations. Only when the extent of the radiogenic injury is great enough to interfere with normal biochemical and metabolic reactions in the body, as for example by interference in enzyme systems or by destruction of tissue, will the metabolism of radioactive compounds differ from that of stable compounds.

For the majority of radioactive isotopes, the limiting dose and maximum permissible rate of intake are determined by the risk of radiogenic injury, rather than by their chemical toxicity. The most important exceptions are natural uranium and soluble forms of uranium-238, uranium-236 and uranium-235 (62). For isotopes with very low specific activities and very long radioactive half-lives (e.g. rubidium-87, indium-115), the limiting dose and maximum rate of intake are determined by their chemical toxicity.

When radioactive elements are ingested or inhaled or enter the body by absorption through the skin, the proportion which enters the blood

stream varies, depending on many factors including the element involved, the chemical composition of the molecules, particle size and density, solubility in body fluids, route of absorption, etc. As a rule, a greater proportion of ingested materials pass through the body unabsorbed than is the case after inhalation. Following absorption into the blood stream or incorporation or fixation in the lung tissues, some radioisotopes are eliminated relatively quickly, via the kidneys or liver. Others tend to concentrate in certain organs of tissues; for example, iodine-131 in the thyroid, radium-226 and strontium-90 in the bone and lead-210 in the kidneys. For a given radionuclide, the critical body organ is that organ of the body whose damage by radiation results in the greatest damage to the body. With very few exceptions it is the organ with the highest concentration of the radionuclide. If the isotope tends to concentrate in the soft tissues and muscles generally, such as cesium-137, the whole body may be regarded as the critical organ. Strictly speaking, determination of the critical organ for a given radionuclide depends on the following criteria:

i) the organ that concentrates the greatest quantity of the nuclide

ii) the dependence of the rest of the body on the particular organ or tissue

iii) the radiosensitivity of the organ or tissue.

For isotopes which are not concentrated in any specific organ but which are spread generally throughout the body tissues, such as tritium, the body as a whole may be regarded as the critical organ.

The risk of radiogenic injury from an inhaled or ingested radioisotope is determined by the dose equivalent in rems delivered to the critical organ. This, in turn, is dependent on the amount of the isotope in the critical organ and the quality of its radiation, including such factors as the relative biological effectiveness (RBE) and the relative damage factor, n. The amount of the isotope in the critical organ at any given time is called the body burden.

Because more was known from clinical observations of the dose-response relationships for radium than for any other internally-deposited nuclide, radium was chosen as the standard for establishing permissible body burdens for other boneseeking radionuclides. An empirically derived standard of 0.1 μCi of radium fixed in the body was recommended as the maximum permissible body burden (MPBB) in 1950. The dose from this amount of radium and its daughters averages about 0.56 rems per week, or about 0.06 rads per week, to the skeleton. From the 0.1 μCi standard for radium and knowledge of the types and energies of radiation emitted by other bone-seeking isotopes, such as strontium-90, and of the fraction of the isotopes in the critical organ in relation to the amount in the whole body, MPBB's have been established for a number of other nuclides.

For isotopes which concentrate in organs other than the bone, or are

distributed throughout the body, a calculation is made of the largest amount (MPBB) of the isotope in question which will not deliver a dose equivalent to the critical organ exceeding 0.3 rems per week. (A more flexible limiting dose is provided by the International Atomic Energy Agency, based on variations in the radiosensitivity of the body organs.) In the IAEA model, the limiting dose may be 0.1, 0.3 or 0.6 rems per week depending on the critical body organ (63).

The mathematics used for calculating the MPBB for an isotope are detailed in ICRP, 1960 (64), or a brief example may be found in Eisenbud, 1973 (12).

The maximum permissible concentrations for a radionuclide in air (MPC_a) and in water (MPC_w) are derived from the MPBB's. The maximum permissible concentration may be defined as the smallest concentration of a radionuclide in air, water or food that, when taken into the body, will deliver a dose equivalent of 0.3 rems per week to the critical organ after 50 years of occupational exposure. It is assumed in the ICRP calculations that the nuclides accumulate in the critical body organ at a rate determined by the amount present in the air, water or food, the rate of ingestion or inhalation, the rate of metabolic transfer to the critical organ, and the rate of elimination of the nuclide from the body.

Radiation from internally deposited sources decreases with time as the result of radioactive decay and biological elimination. The rate of biological elimination varies widely from element to element, just as the radioactive decay rate varies from isotope to isotope. The rate of elimination can be stated in terms of its biological half-life, i.e. the time required for the body to eliminate one-half of the administered quantity of a substance by regular processes of excretion. Stating the elimination in terms of biological half-life is equivalent to saying that elimination follows an exponential curve.

The net effect of combining the biological half-life and the physical half-life gives the effective half-life for each radionuclide, i.e. the period of time required for the radioactivity of the nuclide in the body or organ to fall to half of its original value. (See ICRP 1960 (64) for formulae)

The fraction of a radionuclide taken into the body by ingestion which is transferred to the critical organ (f_w), together with f_a which is the fraction of radionuclide taken into the body by inhalation which reaches the critical organ, are the principal metabolic parameters used in calculating the MPBB and MPC_a and MPC_w for each isotope. Values for the various metabolic parameters for each isotope, and other necessary physiological and anatomical data defining the "standard man" (e.g. amounts of food, water and air intake per day, lung areas and respiratory volumes, etc.), are given in ICRP, 1960 (64) together with equations for calculating the MPBB's and MPC's for air and water.

Assuming that the elimination of radionuclide is exponential, the body burden may be expressed by the equation

$$R_t = A\ e^{-n(\log t)}$$

where R_t is the fraction retained t days after injection of an isotope,

A is the fraction of the injected isotope remaining at the end of unit time,

n is a constant,

e is the base of the natural logarithm.

However, for certain organs, particularly bone, it has been found that the fraction of the body burden excreted per day is best represented by a power function. Following a single injection of certain

radionuclides, the body burden is expressed by the equation

$$R_t = A\ t^{-n}$$

Since ingested or inhaled radionuclides may not be retained to the same degree as injected isotopes, the calculation of the body burden using the power function is modified by the introduction of the appropriate metabolic parameters, e.g. f_1, the fraction of ingested isotope reaching the blood stream.

The ICRP method of computing the MPC's in air and water is based on the exponential model for the accumulation of a radionuclide in the critical organ. From the MPBB the maximum daily intake, P, is first calculated from the equation

$$MPBB = \frac{P\ (1 - e^{-\lambda t})}{\lambda}$$

where $\lambda = 0.693/T$ and T is the effective half-life.

The MPC's for air and water are then calculated from the maximum permissible body intake using the various parameters provided by the definition of the standard man. Again, detailed calculations are shown in ICRP, 1960 (64) and an example is shown in Eisenbud, 1973 (12).

The radionuclides of greatest concern for environmental protection are shown in Table 5.6 in order of increasing mass number, together with their physical and biological half-lives, the mode of exposure, the critical body organ and the MPC_a and MPC_w for each isotope. The MPC's shown are one-tenth that calculated by the ICRP for occupational exposure and apply to persons living in the vicinity of "controlled areas", i.e. in the neighbourhood of nuclear reactor facilities, uranium mills, refineries, etc. For each isotope, the most restrictive MPC has been chosen, as determined by body organ and solubility of the isotope compound.

It will be seen that soluble thorium-230 in air has the most restrictive MPC (8×10^{-5} pCi per litre), and that the gas radon-222 is approximately 10 times more radiotoxic than thoron (radon-220). Comparison of the values shown thus gives an indication of the relative toxicity of the isotopes listed. MPC's have also been derived for certain long-lived isotopes of strontium, radium, plutonium and uranium by the ICRP using the power function model of elimination (64). For the nuclides examined, the power function model gave somewhat higher estimates of the MPC values than does the exponential model. The use of MPC's derived from the exponential model thus appears to give more conservative values for use in radiation protection.

Attention is drawn to a number of ICRP reports which are at present in preparation. These will deal with:

1. Planned and unplanned releases of radioactive materials into the environment,

2. Radon, thoron and their daughter products,

3. Radionuclide decay schemes,

4. Problems involved in developing an index of harm,

5. Limits of intake for radionuclides.

TABLE 5.6
Most Restrictive MPC's for Selected Radionuclides (12, 64)

isotope	major emission	physical half-life	biological half-life	Most restrictive MPC: mode	critical organ	MPC (pCi/l)*
H-3	β^-	12.36 y	9.5 d	air	body tissue	200
				water	body tissue	3×10^6
C-14	β^-	5730 y	total body: 40 d	air-sol	fat	100
			fat: 40 d	water-sol	fat	8×10^5
K-40	β^-	1.26×10^9 y	58 d	-	-	-
				-	-	-
Co-60	β^-	5.26 y	9.5 d	air-insol.	lung	0.3
				water-insol.	GI(LLI)	3×10^4
Sr-89	β^-	50.5 d	bone: 1.8×10^4 d	air {insol.	{lung	
				sol.	bone	1
			whole body: 1.3×10^4 d	water-sol	bone	10^4
Sr-90	β^-	28.1 y	bone: 1.8×10^4 d	air-sol	bone	0.04
			whole body: 1.3×10^4 d	water-sol	bone	400
I-131	β^-	8.05 d	138 d	air-sol	thyroid	0.3
				water-sol	thyroid	2×10^3
Cs-134	β^-	2.5 y	50-150 d	air-insol	lung	0.4
				water-sol	total body	9×10^3
Cs-137	β^-	30 y	50-150 d	air-insol	lung	0.5
				water-sol	total body (liver, spleen)	2×10^4
					muscle	
Pb-210	β^-	22.2 y	bone 10-12 y	air-sol	kidney	4×10^{-3}
				water-sol	kidney, total body	100
Rn-220	α	55 s	-	air	lung	10
				-	-	-
Rn-222	α	3.82 d	-	air	lung	1
				-	-	-
Ra-226	α	1620 y	900 d	air-sol	bone	1×10^{-3}
				water-sol	bone	10
Th-230	α	8.0×10^4 y	bone: 7.3×10^4 d	air-sol	bone	8×10^{-5}
			whole body: 5.7×10^4 d	water-sol	bone	2×10^{-3}
Th-232	α	1.41×10^{10} y	as for Th-230	air-sol	bone	1×10^{-3}
				water-sol	bone	2×10^{-3}
Th-234	β^-	24.1 d	as for Th-230	air-insol	lung	1
				water-sol. insol.	GI(LLI)	2×10^4
U-238	α	4.5×10^9 y	kidney: 15 d	air-sol	kidney	3×10^{-3}
			whole body: 100 d	water-sol	kidney	600

* 1/10th MPC for 168 h week occupational exposure.

References - Health Effects

1. International Commission on Radiological Protection. "Report of Committee I on the evaluation of risks from radiation." "Health Physics", 12, 240 - , 1966.

2. International Commission on Radiological Protection. "Evaluation of radiation doses to body tissues from internal contamination due to occupational exposure". ICRP Publ. No. 10, Pergamon Press, Oxford, 1968.

3. International Commission on Radiological Protection. "Radiosensitivity and spatial distribution of dose." ICRP Pub. No. 14, Pergamon Press, Oxford, 1969.

4. National Academy of Sciences - National Research Council. "The effects on populations of exposure to low levels of ionizing radiation." Nat. Acad. Sci. - Nat. Res. Counc., BEIR Committee Report, Washington, 1972.

5. United Nations Scientific Committee on the Effects of Atomic Radiation." Ionizing Radiation: Levels and Effects. A report of the United Nations Scientific Committee on the Effects of Atomic Radiation to the General Assembly. Volumes I and II." United Nations Publication Sales Nos. E.72.IX.17 and E.72.IX.18, 1972.

6. NCRP Report No. 45. "Natural Background Radiation in the United States." National Council on Radiation Protection and Measurements, Washington, 1975.

7. Buck, C. "Population size required for investigating threshold dose in radiation induced leukaemia." "Science", 129, 1357 - , 1959.

8. National Academy of Sciences - National Research Council. "Health effects of alpha-emitting particles in the respiratory tract," EPA 520/4-76-013. Nat. Acad. Sci. - Nat. Res. Counc., Washington, 1976.

9. Hall, E.J. "Radiobiology for the Radiologist." Harper & Row, Hagerstown, Maryland, 1973.

10. Lloyd, D.C. and Dolphin, G.W. " Radiation-induced chromosome damage in human lymphocytes." "Br. Jour. Indust. Med." 34, 261-273, 1977.

11. Glasstone, S. " The Effects of Nuclear Weapons. U.S. Atomic Energy Commission", Washington, 1962.

12. Eisenbud, M. "Environmental Radioactivity", Academic Press, New York, 1973.

13. Lundin, F.E. Jr., Wagoner, J.K. and Archer, V.E. "Radon daughter exposure and respiratory cancer : Quantitative and temporal aspects. Joint Monograph No. 1", National Institute for Occupational Safety and Health - National Institute of Environmental Health Sciences. U.S. Dept. of Health, Education and Welfare, 1971.

14. Bizzozero, O.J., Johnson, K.G. and Ciocco, A. "Radiation-related leukaemia in Hiroshima and Nagasaki, 1946-1964. I. Distribution, incidence and appearance in time.". New. Eng. Jour. Med. 274, 1095 - 1101, 1966.

15. Okada, S., Hamilton, H.B., Egami, N., Okajima, S., Russell, W.J., and Takeshita, K. (Ed.s). "A review of thirty years study of Hiroshima and Nagasaki atomic bomb survivors." "Jour. Radiation Research Supplement, 1975." The Japan Radiation Research Society, Chiba, Japan.

16. Stewart, A. and Kneale, G.W. " Radiation dose effects in relation to obstetric x-rays and childhood cancers." "Lancet", 1, 1185 - 1188, 1970.

17. MacMahon, B. "Prenatal x-ray exposure and childhood cancer". "Jour. Nat. Cancer Inst." 28, 1173 - , 1962.

18. Mole, R.H. " Ionizing radiation as a carcinogen; practical questions and academic pursuits." "Br. Jour. Radiology", 48, no. 567, 157 - 169, 1975.

19. Saenger, E.L., Thoma, C.E. and Tompkins, E.A. "Incidence of leukaemia following treatment of hyperthyroidism - preliminary report of the Thyrotoxicosis Therapy Follow-Up Study." "Jour. Amer. Med. Assoc.," 205, 855 - 862, 1968.

20. Hempelmann, L.H. "Risk of thyroid neoplasms after irradiation in childhood." "Science", 160, 159 - 165, 1968.

21. National Academy of Sciences - National Research Council. "Long-term effects of ionizing radiations from external sources." Nat. Acad. Sci. - Nat. Res. Counc. Publ. No. 849, Washington, 1961.

22. Pirchan, A. and Sikl, H. "Cancer of the lung in miners in Jackymov (Joachimstal)." "Amer. Jour. Cancer", 16, 681 - 722, 1932.

23. Sevc, J., Kunz, E. and Placek, V. "Lung cancer in uranium miners and long-term exposure to radon daughter products." "Health Physics", 20, 433 - 437, 1976.

24. Muller, J. and Wheeler, W.C. "Causes of death in Ontario uranium miners." In: "Proc. International Symposium on Radiation Protection in Mining and Milling of Uranium and Thorium. Bordeau, France, Sept. 1974." International Labour Office, Geneva, 1976.

25. Ham, J. (Commissioner). "Lung cancer and ionizing radiation in the uranium mines." Report of the Royal Commission on the Health and Safety of Workers in Mines, pp. 66 - 117. Ontario Ministry of the Attorney General, 1976.

26. Hewitt, D. "Appendix C. Radiogenic cancer in Ontario uranium miners, 1955 - 1974." In: "Report of the Royal Commission on the Health and Safety of Workers in Mines", pp. 319 - 329, Ontario Ministry of the Attorney General, 1976.

27. deVillers, A.J., Windish, J.P., Brent, F. deN., Hollywood, B., Walsh, C., Fisher, J.W. and Parsons, W.D. "Mortality experience of the community and of the fluorspar mining employees of St. Lawrence, Newfoundland." "Occupational Health Review," 22, no. 1-2, 1 - 15, 1971.

28. Snihs, J.O. "The approach to radon problems in non-uranium mines in Sweden." Third International Congress of the International Radiation Protection Association, Washington, September 1973.

29. Court Brown, W.M. and Doll, R. "Mortality from cancer and other causes after radiotherapy for ankylosing spondylitis." "Br. Med. Jour.", 2, 1327 - , 1965.

30. Altshuler, B., Nelson, N. and Kuschner, M. "Estimation of lung tissue dose from the inhalation of radon and daughters." "Health Physics," 10, no. 12, 1137 - 1161, 1964.

31. Fry, R.M. "Radon and its hazards." Presented at a symposium at Elliot Lake, Ontario, 1976.

32. Mancuso, T.F., Stewart, A. and Kneale, G. "Radiation exposures of Hanford workers dying from cancer and other causes." "Health Physics," 33, 369 - 385, 1977.

33. Marks, S. and Gilbert, E.S. "Comments on a paper: Radiation exposures of Hanford workers dying of various causes, authored by Mancuso, Stewart and Kneale." Presented at the Health Physics Society Symposium, Saratoga Springs, N.Y., October 1976.

34. Perraud, R., Chameaud, J., Masse, R. and Lafuma, J. "Cancers pulmonaires experimentaux chez le rat apres inhalation de radon a des poussieres non-radioactives." Compt. Rendu, Acad. Sci. Paris, 270, 2594 - 2595, 25 Mai 1970.

35. Bair, W.J. "Inhalation of radionuclides and carcino-genesis." In: "Inhalation Carcinogenesis." U.S. Atomic Energy Commission Symposium Series No. 18, Oak Ridge, 1970.

36. Sanders, C.L. Jr., Thompson, R.C. and Bair, W.J. "Lung cancer: dose response studies with radionuclides." In: "Inhalation Carcinogenesis." U.S. Atomic Energy Commission Symposium Series No. 18, Oak Ridge, 1970.

37. Evans, R.D. "Radium in man." "Health Physics", 27, 497 - 510, 1974.

38. Speiss, H. and Mays, C.W. "Bone cancers induced by Ra-224 (Th-X) in children and adults." "Health Physics" 19, 713 - 729, 1970.

39. Evans, R.D. and Dudley, R.A. "The radium-226 standard (0.1 microgram) for bone-seekers." Joint Committee on Atomic Energy, Congress of the United States Publication No. 437, 1960.

40. Dougherty, T.F. and Mays, C.W. "Bone cancer induced by internally-deposited emitters in beagles." In: "Radiation-Induced Cancer." Proceedings of a Symposium in Athens, International Atomic Energy Agency, Vienna, 1969.

41. Rowland, R.E., Faila, P.M. Keane, A.T. and Stehney, A.F. "Some dose-response relationships for tumour incidence in radium patients." "Argonne National Laboratory Radiological Physics Division Annual report," Center for Human Radiobiology, ANL-7760, Part II, 1 - 17, July, 1969 -June 1970.

42. Mays, C.W., Jee, W.S.S., Lloyd, R.D., Stover, B.J., Dougherty, T.F., Taylor, G.N., Christensen, W.R., Dougherty, J.H. and Atherton, D.R. "Radiation induced bone cancer in beagles." In: "Delayed Effects of Bone-Seeking Radionuclides." University of Utah Press, Salt Lake City, 1969.

43. Mays, C.W. and Lloyd, R.D. "Bone sarcoma risk from Strontium-90." In: "Biomedical Implications of Radiostrontium Exposure (L.K. Bustad and M. Goldman, Eds)." Div. Tech. Inform., U.S. Atomic Energy Agency, Washington, 1972 (a).

44. Mays, C.W. and Lloyd, R.D. "Bone sarcoma incidence vs. alpha particle dose." In: "The Radiobiology of Plutonium" (B. Stover and W.S.S. Jee, Eds.), J.W. Press, University of Utah, Salt Lake City, 1972 (b).

45. Hulse, E.V., Mole, R.H. and Papworth, G.D. "Radio-sensitivities of cells from which radiation induced skin tumours are derived." "Int. Jour. Radiation Biology" 14, no. 5, 437 - 444, 1968.

46. Stewart, A., Webb, J. and Hewitt, D. "A survey of childhood malignancies." "Br. Med. Jour." 1, 1495 - , 1958.

47. Mole, R.H. "Antenatal irradiation and childhood cancer: causation or coincidence?" "Br. Jour. Cancer", 30, 199 - 208, 1974.

48. Jablon, S. and Kato, H. Childhood cancer in relation to prenatal exposure to atomic-bomb radiation. Lancet, 2, 1000 - 1003, 1970.

49. Graham, S. "Preconception, intrauterine and postnatal irradiation as related to leukaemia." "Nat. Cancer Institute Monograph" 19, 347 -371, 1966.

50. Gibson, R. "Leukaemia in children exposed to multiple risk factors." "New. Eng. Jour. Med." 279, 906 - 909, 1968.

51. Bross, I.D.J. and Natarajan, N. "Risk of leukaemia in susceptible children exposed to preconception in utero, and postnatal radiation." "Preventive Medicine", 3, 361 - 369, 1974.

52. Bross, I.D.J. and Natarajan, N. "Genetic damage from diagnostic radiation." "Jour. Amer. Med. Assoc." 22, 2399 - 2401, May, 1977.

53. Newcombe, H.B. "Public health aspects of radiation." Document prepared for the Science Council of Canada's Study on "Policies and Poisons". Atomic Energy Agency of Canada Limited, Chalk River, Ontario, 1976.

54. Pochin, E.E. "Estimated population exposure from nuclear power production and other radiation sources." Nuclear Energy Agency - Organization for Economic Co-operation and Development, Paris, 1976.

55. Modan, B., Baidatz, D., Mart, H., Steinitz, R. and Levin, S.G. "Radiation-induced head and neck tumours." "Lancet" 1, 277 - 279, 1974.

56. Seltser, R. and Sartwell, P.E. "The influence of occupational exposure to radiation on the mortality of American radiologists and other medical specialists." "Amer. Jour. Epidem.", 81, 2 - 22, 1965.

57. McKusick, V.A. "Mendelian Inheritance in Man." 3rd Edn. Johns Hopkins Press, Baltimore, 1971.

58. Freire-Mais, A. Krieger, H. "Human genetic studies in areas of high natural radiation. IX. Effects on mortality, morbidity and sex ratio." "Health Physics", 34, 61 - 65, 1978.

59. Spalding, J.F., Brooks, M.R. and Tietjen, G.L. "Lifetime body weights and mortality distribution in mice with 10 to 35 generations of ancestral x-ray exposure." "Genetics", 63, 897 - 906, 1969.

60. Boyd, J.T., Doll, R., Faulds, J.S. and Leiper, J. "Cancer of the lung in iron ore (hematite) miners." "Br. Jour. Indust. Med.", 27, no. 2, 97 - 105, 1970.

61. Frigerio, N.A, Eckerman, K.F. and Stowe, R.S. "The Argonne Radiological Impact Program (ARIP). Part I. Carcinogenic hazard from low-level, low-rate radiation." ANL/ES Part I, Environmental and Earth Sciences, Argonne National Laboratory, Argonne, Ill., Sept. 1973.

62. International Commission on Radiological Protection. "Recommendations of the International Commission on Radiological Protection" (as amended 1959 and revised 1962). ICRP Publication No. 6, Pergamon Press, Oxford, 1964.

63. IAEA. "A basic toxicity classification of radionuclides." International Atomic Energy Agency, Technical Report Series No. 15, Vienna, 1963.

64. International Commission on Radiological Protection. "Report of Committee II on permissible dose for internal radiation." ICRP Publication No. 2, Pergamon Press, Oxford, 1960. "Health Physics," 3, 1 - 1960.

Radiation Protection Criteria 6

Introduction

Partially as the result of the increasing use of nuclear energy, and partially as a result of elevated levels of natural radioactivity in housing, there is considerable interest in the adequacy of existing radiation protection criteria. In Canada, the Atomic Energy Control Board (AECB) is responsible for regulating the production, application and use of all aspects of atomic energy. Under proposed new legislation, which has been introduced in the Commons, the Nuclear Control Board (NCB) would replace the AECB and assume responsibility for enforcement of regulations dealing with health, safety, security and environmental matters. The promotional aspects of nuclear energy would continue to be directed by the Department of Energy, Mines and Resources.

The Canadian regulations for radiation protection are based on the recommendations of an international body - The International Commission on Radiological Protection (ICRP). Since the Canadian regulations are based on the recommendations of the ICRP, the following section will outline some of the more important developments in these radiation protection standards, and the existing Canadian standards.

6.1 Historical Evolution

The ICRP was first established as the International Committee of X-ray and Radium protection under the auspices of the Second International Conference of Radiology held in Stockholm in 1928. This committee was charged with "formulating recommendations for the protection of the members of the Congress in the practice of their Art and Science" (1). It has been noted in the literature, that, "In fact, from 1896 until about 1956, it could be said that the major attention for all of the established radiation protection bodies was directed to what we could classify as occupational exposure. Beginning about the mid-1950's, major attention began to be directed toward exposure of the public, largely as a result of the possible deleterious radiation effects of weapons testing" (2).

During the 1950's, a number of organizations undertook intensive evaluations of the problems of population exposure particularly with regard to genetic effects. The most recent recommendation of the ICRP suggests that "Radiation protection is concerned with the protection of individuals, their progeny and mankind as a whole while still allowing necessary activities from which radiation exposure might result." (3, Para 6). Furthermore, the ICRP states that the aim of radiation protection should be "to prevent detrimental, non-stochastic effects and limit the probability of stochastic effects to levels deemed to be acceptable" (3, Para 9). This clearly suggests that quantitative radiation protection standards cannot be established on the basis of scientific evidence alone, but must of necessity require an evaluation of many societal factors, such as politics, economics, morality, national defence, the indirect prevention of other kinds of injury, (eg. from alternative fuel cycles), the national well-being, etc.

In order to clarify this aspect of the basis for setting radiation protection standards, it is appropriate to digress and briefly discuss the concept of risk. Everyone is continuously subject to risks from well-known environmental hazards such as arsenic, vinyl chloride and atmospheric particulates. People are also exposed to potential hazards from natural and manmade radiation. There does, however, appear to be a difference in the way in which the public perceives the risks associated with exposure to radioactivity from the risks associated with other environmental contaminants. The ICRP (3, Para. 118) suggest that, based on their review of available information related to risks regularly accepted in everyday life, a probability of fatal risks to the general public in the order of 10^{-6} to 10^{-5} per year "would likely be acceptable to any individual member of the public" (3, Para. 118).

The estimated risk of dying from radiation-induced cancers (about 1 per 100,000) (3, Para. 60) which arises from exposure to 100 mrem per year of radioactivity is approximately equivalent to the risk of dying by being struck by a bolt of lightning or by being electrocuted. Further data on everyday risks to which people are exposed is summarized in Table 6.1. It is worth noting that there is a considerable amount of published data concerning comparisons between the risk associated with alternate fuel cycles (eg. 4) and thus, it is important that indirect

TABLE 6.1 (5)

AVERAGE RISK OF VARIOUS CAUSES OF FATALITY

Accident Type	Total Number	Individual Chance Per Year
Motor Vehicles	55,791	1 in 4,000
Falls	17,827	1 in 10,000
Fires and Hot Substances	7,451	1 in 25,000
Drowning	6,181	1 in 30,000
Firearms	2,309	1 in 100,000
Air Travel	1,778	1 in 100,000
Falling Objects	1,271	1 in 160,000
Electrocution	1,148	1 in 160,000
Lightning	160	1 in 2,000,000
Tornadoes	91	1 in 2,500,00
Hurricanes	93	1 in 2,500,000
All Accidents	111,992	1 in 1,600
Nuclear Reactor Accidents (100 plants)		1 in 5,000,000,000

consequences associated with potential over-regulation of the nuclear program should be taken into account in decisions as to the optimum source of increased power production.

Up to the 1920's and early 1930's, the idea of a "tolerance" dose of radiation was based on the production of skin erythema (reddening of the skin, similar to mild sunburn). This particular biological response to ionizing radiation was of special interest in that it is a threshold-type phenomenon and it is dose-rate dependant. "Because there was a threshold below which erythema was not produced, it is natural to think that there could be a tolerance dose for other biological responses to x-rays below which no effect would be produced. Because of the clearly demonstrated recovery factor, when dose to skin was fractionated in time, it was natural to think, too, that a daily tolerable dose might be repeated regardless of the total dose in a lifetime" (1). By 1934, the ICRP had recommended a tolerance dose of 0.2 R/day. In the United States, the National Commission on Radiological Protection (NCRP) had "reviewed the basic data and since the errors in this data were so large, had rounded the tolerance dose down to 0.1 R/day" (2). It is important to note, that for the first time, there was a quantitive value for a permissible radiation dose for radiation workers. It is worth noting that all values for permissible dose to radiation workers up to the present have been derived from these early proposals. "Out of all of this it is essential to note that through all of this work there has been no injury or effect of any kind observed among people who might have been exposed to such levels of radiation. It is therefore crucial to our understanding to realize that any translation from that early background to our present number system has been derived on the basis of the exercise of good judgment" (2).

In 1949, the NCRP reviewed the radiation exposure problem in view of the large changes which were expected to occur as a result of the discovery of atomic energy. Principally, because many more people were expected to be exposed in a wide variety of ways, the NCRP recommended lowering the permissible dose to radiation workers from 0.1 R/day to 0.3 R/week, roughly a factor of 2 (2). The ICRP recommended continued use of the basic value of the permissible dose of 0.3 R/week for whole body radiation of radiation workers in 1953. Industry, as a matter of practice, has been setting its administrative permissible levels substantially lower than the regulatory levels so as to avoid the possibility of overrun. "This practice has led to a situation where each time, and for whatever reason, there may be some pressure to lower the exposure levels, it can usually be shown that this lowering would not exert any hardship on industry because they are already maintaining lower exposure levels." (2). It must be noted, however, that each time the exposure standards are lowered, there is a concomitant associated cost which is, of necessity, passed on to the consumer.

With regard to the Canadian situation, it is apparent that the Ontario Hydro operating objective, whereby Ontario Hydro attempts to operate its nuclear reactors such that the critically exposed individual receives no more than about 1% of the regulatory dose limit, appears to have been

adopted by the regulatory bodies as a de-facto regulatory objective (at least in the public's mind).

By 1958, the ICRP had given special recognition to the problem of radiation exposure to the general population. "The ICRP discussion of genetic dose problem was expressed in somewhat tentative terms because it was obvious that no group had yet had time to really evaluate British and American reports in depth. In concept, the permissible genetic dose was defined as that dose, which if it were received by each person from conception to the age of child-bearing, would result in an acceptable burden to the whole population. The report then went on to indicate that the genetic dose to the population could be assessed as the annual genetically significant dose multiplied by the mean age of child-bearing which, for the purpose of their recommendation, would be taken as 30 years." (6) It was suggested that the genetic dose for the whole population from all sources additional to natural background should not exceed 5 rems plus the lowest practicable contribution from medical exposure. This meant 5 rems distributed over a 30-year period.

In its most recent recommendation, the ICRP concluded that "It has become increasingly clear that the previously suggested level is not likely to be reached and it is very improbable that responsible authorities would permit the average dose equivalent in a population to reach values that are more than small fractions of the former genetic dose limit of 5 rem in 30 years. Therefore, continuance of the former genetic dose limit could be regarded as suggesting the acceptability of a higher population exposure than is either necessary or probable." (3, Para. 129)

The ICRP recommendations also state that "each man-made contribution to population exposure has to be justified by its benefits and that limits for individual members of the public refer to the total dose equivalent received from all sources". (3, Para. 130) 'All sources' in relation to dose equivalents limits, does not include contributions from medical procedures or from normal, natural radiation. (3, Para. 83) In summary, then, the ICRP recommended the continued use of the whole body dose equivalent limit of 0.5 rem/year as applied to critical members of the general public.

6.2 Philosophy of Radiation Protection Criteria

In essence, the current philosophy of radiation protection appears to be a system of dose limitation in which all radiation exposures are kept As Low As Reasonably Achievable, economic and social factors being taken into account - the ALARA principle (eg. ICRP 26, 3).

Implicit in such a system of dose limitation is the requirement that it is necessary to make value judgements comparing the human health costs associated with radiation exposure to various economic and social benefits. Unfortunately, many of the important problems facing the decision-maker today are those for which there is very little data, such as the effect of today's radiation exposure ten or twenty generations in the future, the consequences of a nuclear accident, or the build-up of nuclear waste. In cases such as these, benefit cost analyses cannot be done in terms of dollars or other common units but rather must identify issues and study the possible extreme ranges of benefits or costs arising from a given course of action.

In undertaking such analyses, or in assessing the risks associated with radiation exposure, it is conventional to use linear extrapolations of dose and effect. It is important to emphasize however, that, "the use of linear extrapolations from the frequency of effects observed at high doses may suffice to assess an upper limit of risk, with which the benefit of a practice, or the hazard of an alternative practice - not involving radiation exposure - may be compared. However, the more cautious such an assumption of linearity is, the more important it becomes to recognize that it may lead to an over-estimate of the radiation risk, which in turn could result in a choice of alternatives that are more hazardous than practices involving radiation exposures. Thus, in the choice of alternative practices, radiation risk estimates should be used only with great caution and with explicit recognition of the possibility that the actual risk at low doses may be lower than that implied by a deliberately cautious assumption of proportionality." (3, Para. 30)

6.3 Radiation Dose Limits For The Public

The AECB has issued radiation dose limits based on the recommendations of the ICRP. The dose limits for a member of the public at large are set at one-tenth (1/10) of the limit for a radiation worker. These limits, shown in Table 6.2, do not apply to exposure to radiation arising from natural sources of radioactivity or from medical exposures. Both internal and external sources of exposure to radiation are taken into account in estimating radiation doses.

It is often necessary to provide limits associated with quantities other than dose equivalents particularly when dealing with environmental situations. When such limits are related to the basic dose limits by a specified model which reflects both the environmental situation and the basic limits, they are called derived limits. For example, derived limits can be set for quantities such as dose equivalent rate in the work place, at home, etc. or in terms of maximum permissible concentrations of various radioisotopes in the air or in the water, or some fraction thereof, which can be taken as some form of investigation or action level. Ontario Hydro, for example, has developed a system of derived release limits for controlling the radiation doses arising from the gaseous and liquid effluent from its nuclear generating stations (8). Provided effluents from nuclear stations are maintained at or below the desired level, the radiation dose to members of the public living at the station boundary will also be at or below the regulatory limit.

TABLE 6.2

RADIATION DOSE LIMITS FOR
AN INDIVIDUAL MEMBER OF THE PUBLIC (a)

Organ, Tissue	Current Standard (b) mrem/y
Whole Body, Gonads, Bone Marrow	500
Bone, Skin, Thyroid	3000 (c)
Any Tissue of Hands, Forearms, Feet and Ankles	7500
Other Single Organs or Tissues	1500

RADON DAUGHTER EXPOSURE LIMIT
FOR AN INDIVIDUAL MEMBER OF THE PUBLIC (d)

Organ	WLM/y (e)
Lungs	0.4

(a) Ref. 7
(b) Current AECB objective for new facilities is to achieve 1% of these limits.
(c) For children under 16, the thyroid limit is 1500 mrem/y.
(d) Ref. 7
(e) WLM/y = Working level months per year.

6.4 Summary and Discussion

The ALARA principle of maintaining radiation doses at levels "as low as reasonably achievable, economic and social factors taken into account" is the basic tenet of the philosophy of radiation protection. A linear relation between radiation dose and response is conventionally used in estimating the potential risks associated with radiation exposure. This assumption may provide an overestimate of the actual risk and hence must be used with caution when comparing the risks associated with radiation exposure to other risks.

Although the existing radiation protection standards are generally believed to provide an adequate margin of safety, some researchers believe that the present standards are too high by about one order of magnitude. For example, the recent study of Hanford workers suggests that there may be a greater risk from low levels of ionizing radiation than previously suspected (9). Other researchers have questioned this conclusion for a variety of reasons, including faulty epidemiology and inadequate dosimetry (10, 11, 12). Even if it is eventually established that the dose limits are too high, the risk to the general population would still be statistically small. Whether or not man-made radiation exposure would be 'acceptable' in such a setting would then (as now) depend on the public's perception of radiation risks when compared to the effects of other environmental agents.

References - Radiation Protection Criteria

1. Stewart, C. G., "Perspectives in the Field of Radiation Protection". "Seminar on the Environmental Impact of the Disposal of Radioactive Material, Toronto, 1976". Pub. No. EE-4. Toronto: University of Toronto, Institute for Environmental Studies, 1977.

2. Taylor, Lauriston S., "The Origin and Significance of Radiation Dose Limits for the Population". WASH-1336. Washington, D.C., U.S. Atomic Energy Commission, Division of Biomedical and Environmental Research, 1973.

3. International Commission on Radiological Protection. "Recommendations of the International Commission on Radiological Protection". ICRP Publication 26. Oxford: Permagon Press, 1977.

4. Gotchy, R. L., "Health Effects Attributable to Coal and Nuclear Fuel Cycles Alternatives, Draft". NUREG-0332. Washington, D.C.: U.S. Nuclear Regulatory Commission, Division of Site Safety and Environmental Analysis, 1977.

5. U.S. NRC, "Reactor Safety Study: An Assessment of Accident Risks in U.S. Commercial Nuclear Power Plants". U.S. Nuclear Regulatory Commission, October 1975.

6. Taylor, Lauriston S., "Radiation Protection Standards". Cleveland, Ohio: Chemical Rubber Company Press, 1971.

7. Atomic Energy Control Regulations, "Canada Gazette Part II". 112 (January 1978): 406-411.

8. Wong, K. Y., "Basis for the Derived Limits for the Release of Radionuclides in gaseous and liquid effluents from Ontario Hydro's Nuclear Stations". H.P.D.-73-6. Toronto: Ontario Hydro, 1973.

9. Mancuso, T. F., A. Stewart and G. Kneale, "Radiation Exposures of Hanford Workers Dying from Cancer and Other Causes". Health Physics 33 (November 1977): 369-385.

10. Anderson, Terence W., "Radiation Exposures of Hanford Workers: A Critique of the Mancuso, Stewart and Kneale Report". Submitted to Health Physics, February 1978.

11. Marks, Sidney and Gilbert, Ethel S., "Comment on Paper: 'Radiation Exposures of Hanford Workers Dying of Various Causes'." "Midyear Symposium of the Health Physics Society, 10th, Saratoga Springs, N.Y., 1976". n.p., n.d.

12. Reissland, T.A. and G. W. Dolphin, "Radiation Exposures of Hanford Workers Dying from Cancer and Other Causes", U.K. National Radiation Protection Board, 1977.

Monitoring 7

7.1 Monitoring Objectives

The primary objective of radiological monitoring in the vicinity of nuclear facilities is to obtain the information necessary for assessing the population radiation exposure. The monitoring data can also be used for other purposes such as determining compliance with regulations, identifying sources of specific contaminants, predicting trends, or for public relations.

Environmental monitoring is generally oriented toward assessing the population dose from normal operations. Nevertheless, monitoring programs should also provide a data base suitable for assessing radiation doses resulting from non-routine releases.

In addition to direct radiation exposure from a nuclear facility or from ground shine from radionuclides deposited on the ground, it is necessary to determine the concentration of radionuclides present in the various ingestion and inhalation pathways (see Figure 1.5) and then use mathematical models to convert these concentrations to radiation doses. For many nuclear facilities the external dose and concentration of radionuclides in environmental media attributable to the nuclear facility are within natural background variations. Even in this situation, it remains necessary to verify the adequacy of the computational models with field programs.

In view of the large body of reports available in the literature concerning the objectives of, and design of monitoring programs (e.g. 1, 2, 3, 4) it is not felt necessary to elaborate further on this topic. It is perhaps appropriate, however, to briefly identify some of more important factors which may affect the design of a routine survey (monitoring program) for radioactivity or radiation outside the facility boundaries. These factors include: (4, Para. 25)

"(a) The type of installation and the potential hazard associated with it.

(b) The nuclides to be released, their activity, their physical and chemical form, and the method and route of release.

(c) The existing or expected presence of these nuclides from other sources.

(d) The behaviour of the released nuclides in the environment.

(e) Natural features of the environment which affect the behaviour of released nuclides, e.g. climate, topography, pedology, geology, hydrology and hydrography, and vegetative cover.

(f) Man-made features of the environment which affect the behaviour of released nuclides, e.g. reservoirs, regulated streams or rivers, and harbour installations.

(g) The utilization of the environment for agriculture, fisheries, water and food supplies, industry and recreation.

(h) The population distribution and habits."

It is also worth noting that pre-operational studies can provide information on those factors listed above for which satisfactory data does not already exist. With regard to monitoring programs the principal objectives of pre-operational studies are: (4, Para. 26)

"(a) Obtaining information on the critical nuclides, pathways and groups, thus leading to the design of the operational survey and to the provision of the quantitative basis for interpreting the results in terms of the actual or potential exposure of man.

(b) Providing information on the preoperational level of radiation and radioactivity in the environment, in cases where this information is helpful in interpreting operational surveys.

(c) Testing and exercising operational survey methods and procedures."

7.2 Existing Monitoring Programs

Nuclear installations are designed and operated to contain radioactive materials and radiation. Nevertheless, some release of radioactivity occurs to various environmental media, and the amounts and composition of the releases vary from installation to installation. Thus, the environmental pathways by which each of the released radionuclides reaches man depends not only on the type of facility, but also on the local environment.

"Experience has shown that a study of the situation will indicate that certain nuclides and certain exposure pathways are much more important than others. These nuclides and pathways are designated 'critical' " (4, para. 14). Usually one or two groups of people will receive doses higher than those received by the average population as the result of living habits, location or age etc. Hence, the various environmental monitoring programs vary widely from facility to facility depending on emission characteristics, environmental pathways, and analysis and identification of critically exposed populations.

Although it has not been possible, during this study, to obtain and compile actual monitoring data from operators of nuclear facilities in Ontario, an attempt was made to identify existing monitoring programs, and the parameters monitored. These data are summarized in Appendix II. To the extent possible, the environmental radioactivity program carried out in Ontario by the various regulatory agencies is also summarized in Appendix II. In addition, some data which describes the various nuclear operations and their concomitant effluents and emissions are also available in the literature. At the present time, we are not aware of any radiological monitoring of industrial facilities that use radio-isotopes.

The AECB has established an environmental monitoring advisory committee to review the monitoring requirements for nuclear facilities in Canada. This committee consists of representatives of universities, the Atomic Energy Control Board of Canada, Environment Canada, provincial agencies, independent consultants and the private sector. This committee has already reviewed a number of monitoring programs for new facilities, and is compiling an index of all radiological monitoring being conducted in Canada. This work is to be completed by the end of 1978.

7.3 Monitoring Procedures and Equipment

Although methods and equipment are continuously being improved, the analytical techniques used to identify radioactive elements are well established, as is instrumentation for radiological monitoring. An excellent reference book is "Instrumentation for Environmental Monitoring", a three volume set put out by the Lawrence Berkeley Lab. This volume is regularly updated and so contains the most recent technology available. The reader is also referred to "Standard Methods for Examination of Water and Wastewater, 14th edition" published by A.W.W.A. in 1975, and to the bibliography appended to this report.

References - Monitoring

1. Moella, D. W., J. M. Selby, D. A. Waite, J. P. Corley, "Environmental Surveillance for Nuclear Facilities", Nuclear Safety Volume 19, No. 1, January - February 1978 pp 66-79.

2. United States Environmental Protection Agency, "Environmental Radioactivity Surveillance Guide", Office of Radiation Programs USEPA, June 1972 (PB-220-472).

3. International Atomic Energy Association, "Objectives and Design of Environmental Monitoring Programs for Radioactive Contaminants", IAEA Safety Series No. 41, 1975.

4. International Commission on Radiological Protection, "Principles of Environmental Monitoring related to the Handling of Radioactive Materials", ICRP Publication No. 7 (1965).

APPENDIX I

(GLOSSARY)

GLOSSARY

Activity: The number of nuclear transformations occurring in a given quantity of material per unit time.

ALARA: The current philosophy of radiation protection. This is a system of dose limitation in which all radiation exposures are kept as low as reasonably achievable, economic and social factors being taken into account.

Alpha Particle: A charged particle emitted from the nucleus of an atom having a mass and charge equal in magnitude to a helium nucleus i.e., two protons and two neutrons.

Anion: Negatively charged ion.

Atom: Smallest particle of an element which is capable of entering into a chemical reaction.

Atomic Number: The number of protons in the nucleus of a neutral atom of a nuclide. The "effective atomic number" is calculated from the composition and atomic numbers of a compound or mixture. An element of this atomic number would interact with the photons in the same way as the compound or mixture (Symbol Z).

Atomic Weight: The weighted mean of the masses of the neutral atoms of an element expressed in atomic mass units.

Beta Particle: Charged particle emitted from the nucleus of an atom, with a mass and charge equal in magnitude to that of the electron.

Cation: Positively charged ion.

Curie: The special unit of activity. One curie equals 3.7×10^{10} nuclear transformations per second (Abbreviated Ci). Several fractions of the curie are in common usage.

Microcurie: One-millionth of a curie (3.7×10^4 disintegrations per sec)(μCi)

Millicurie: One-thousandth of a curie (3.7×10^{7} disintegrations per sec)(mCi)

Picocurie: One-millionth of a microcurie (3.7×10^{-2} disintegrations per second or 2.22 disintegrations per minute) (pCi).

Daughter: Synonym for decay product.

Decay, Radioactive: Disintegration of the nucleus of an unstable nuclide by spontaneous emission of charged particles and/or electromagnetic energy.

Decay Constant: The fraction of the number of atoms of a radioactive nuclide which decay in unit time (Symbol: λ).

Decay Product: A nuclide resulting from the radioactive disintegration of a radionuclide, formed either directly or as the result of successive transformations in a radioactive series. A decay product may be either radioactive or stable.

Derived Release Limit: The DRL's are maximum limits for the radioactivity that may be released. They are derived from the maximum radiation dose permitted to an individual member of the public.

Dose: A general form denoting the quantity of radiation or energy absorbed. For special purposes it must be appropriately qualified. If unqualified it refers to absorbed dose.

Absorbed Dose: The energy imparted to matter by ionizing radiation per unit mass of irradiated material at the place of interest. The unit of absorbed dose is the rad. One rad equals 100 ergs per gram.

Cumulative Dose: The total dose resulting from repeated exposures to radiation.

Dose Equivalent (DE): A quantity used in radiation protection. It expresses all radiations on a common scale for calculating the effective absorbed dose. It is defined as the product of the absorbed dose in rads and certain modifying factors. The unit of dose equivalent is the rem.

Maximum Permissible Dose Equivalent (MPD): The greatest dose equivalent that a person or specified part thereof shall be allowed to receive in a given period of time.

Permissible Dose: The dose of radiation which may be received by an individual within a specified period with expectation of no significantly harmful result.

Threshold Dose: The minimum absorbed dose that will produce a detectable degree of any given effect.

Dose Rate: Absorbed dose delivered per unit time.

Dosimeter: Instrument to detect and measure accumulated radiation exposure.

Electron: A stable elementary particle having a negative electric charge equal to 1.60210×10^{-19}C. and a rest mass equal to 9.1091×10^{-31} kg.

Element: A category of atoms all of the same atomic number.

End Product: The stable nuclide that is the final member of a radioactive series.

Equilibrium, Radioactive: In a radioactive series, the state which prevails when the ratios between the amounts of successive members of the series remains constant.

Fallout: Radioactive debris from a nuclear detonation, which is airborne or which has been deposited on the earth. Special forms of fallout are "Dry Fallout", "Rainout", and "Snowout".

Gamma Ray: Short wavelength electromagnetic radiation of nuclear origin (range of energy from 10 keV to 9 MeV) emitted from the nucleus.

Gram-Rad: Unit of integral dose equal to 100 ergs.

Half-Life, Biological: The time required for the body to eliminate one-half of an administered dosage of any substance by regular processes of elimination. Approximately the same for both stable and radioactive isotopes of a particular element.

Half-Life, Effective: Time required for a radioactive element in an animal body to be diminished 50 percent as a result of the combined action of radioactive decay and biological elimination.

Effective half-life $= \frac{\text{Biological half-life x Radioactive half-life}}{\text{Biological half-life + Radioactive half-life}}$

Half-life, Radioactive: Time required for a radioactive substance to lose 50 percent of its activity by decay. Each radionuclide has a unique half-life.

Ion: Atomic particle, atom, or chemical radical bearing an electrical charge, either positive or negative.

Ionization: The process by which a neutral atom or molecule acquires a positive or negative charge.

Isotopes: Nuclides having the same number of protons in their nuclei, and hence the same atomic number, but differing in the number of neutrons, and therefore in the mass number. Almost identical chemical properties exist between isotopes of a particular element. The term should not be used as a synonym for nuclide.

Mass Number: The number of nucleons (protons and neutrons) in the nucleus of an atom (Symbol: A)

Molecular Weight: The sum of the atomic weights of all the atoms in a molecule.

Molecule: Smallest quantity of a compound which can exist by itself and retain all properties of the original substance.

Muon: A meson is any one of several elementary particles having a mass intermediate between that of an electron and a proton, either a negative or a positive charge, and a spin of 1/2 or 0. A muon, or mu meson, is a specific meson having a mass approximately 207 times that of an electron, with positive or negative charge and spin of 1/2.

Nucleon: Common name for a constituent particle of the nucleus. Applied to a proton or neutron.

Nuclide: A species of atom characterized by the constitution of its nucleus. The nuclear constitution is specified by

the number of protons(Z), number of neutrons(N), and energy content; or, alternatively, by the atomic number(Z), mass number A = (N+Z), and atomic mass. To be regarded as a distinct nuclide, the atom must be capable of existing for a measurable time. Thus, nuclear isomers are separate nuclides, whereas promptly decaying excited nuclear states and unstable intermediates in nuclear reactions are not so considered.

Parent: A radionuclide which, upon disintegration, yields a specified nuclide - either directly or as a later member of a radioactive series.

Positron: Particle equal in mass to the electron and having an equal but positive charge.

Proton: Elementary nuclear particle with a positive electric charge equal numerically to the charge of the electron and a mass of 1.007277 mass units.

Quality Factor (QF): The linear-energy-transfer-dependent factor by which absorbed doses are multiplied to obtain (for radiation protection purposes) a quantity that expresses - on a common scale for all ionizing radiations - the effectiveness of the absorbed dose.

Rad: The unit of absorbed dose equal to 0.01 J/kg in any medium. (See Absorbed Dose.)(Written: rad.)

Radiation: (1) The emission and propagation of energy through space or through a material medium in the form of waves; for instance, the emission and propagation of electromagnetic waves, or of sound and elastic waves.
(2) The energy propagated through space or through a material medium as waves; for example, energy in the form of electromagnetic waves or of elastic waves. The term radiation or radiant energy, when unqualified, usually refers to electromagnetic radiation. Such radiation commonly is classified, according to frequency, as Hertzian, infra-red, visible (light), ultra-violet, x ray, and gamma ray. (See Photon.)
(3) By extension, corpuscular emissions, such as alpha and beta radiation, or rays of mixed or unknown type, as cosmic radiation.

Background Radiation: Background radiation due to cosmic rays and natural radioactivity is always present. Indoors, there may also be background radiation due to the presence of radioactive substances in other parts of the building, in the building material itself, etc.

External Radiation: Radiation from a source outside the body - the radiation must penetrate the skin.

Internal Radiation: Radiation from a source within the body (as a result of deposition of radionuclides in body tissues).

Radioactivity: The property of certain nuclides of spontaneously emitting particles or gamma radiation or of emitting x-radiation following orbital electron capture or of undergoing spontaneous fission.

Artificial Radioactivity: Manmade radioactivity produced by particle bombardment or electromagnetic irradiation, as opposed to natural radioactivity.

Induced Radioactivity: Radioactivity produced in a substance after bombardment with neutrons or other particles. The resulting activity is "natural radioactivity" if formed by nuclear reactions occurring in nature and "artificial radioactivity" if the reactions are caused by man.

Natural Radioactivity: The property of radioactivity exhibited by more than fifty naturally occurring radionuclides.

Rem: A special unit of dose equivalent. The dose equivalent in rems is numerically equal to the absorbed dose in rads multiplied by the quality factor, the distribution factor, and any other necessary modifying factors.

Rep: An obsolete special unit of absorbed dose.

Roentgen(R): The special unit of exposure. One roentgen equals 2.58×10^{-4} coulombs per kilogram of air.

Series, Radioactive: A succession of nuclides, each of which transforms by radioactive disintegration into the next until a stable nuclide results. The first member is called the "parent," the intermediate members are called "daughters," and the final stable member is called the "end product."

Specific Activity: Total activity of a given nuclide per gram of a compound, element, or radioactive nuclide.

Working Level Month	A unit of integrated exposure. Breathing air with a concentration of 1 WL for the working hours in a month (taken as 170 hours) results in an exposure of 1 WLM.
WLM/annum:	A unit of exposure rate. An exposure rate of 4 WLM/annum will result from working 170 hours/month for 12 months in an atmosphere with a daughter product concentration of 0.33 WL.
X Rays:	Penetrating electromagnetic radiations whose wavelengths are shorter than those of visible light. They are usually produced by bombarding a metallic target with fast electrons in a high vacuum. In nuclear reactions, it is customary to refer to photons originating in the nucleus as gamma rays, and those originating in the extranuclear part of the atom as x rays. These rays are sometimes called roentgen rays after their discoverer, W.C. Roentgen.

Reference: Radiological Health Handbook - U.S. Dept. of Health, Education & Welfare, January, 1970.

APPENDIX II

(MONITORING PROGRAMS)

MONITORING INFORMATION SHEETS

This is an attempt to summarize current, ongoing monitoring programs. Some completed programs have been included, when their results have not yet been published. Programs on the provincial, federal, international and industrial level have been included.

Originally, the plan was to make summaries of the results of radiological environmental monitoring in Ontario. However, it soon became apparent that there was not enough time to obtain all of this information. It was then decided that a summary of all of such monitoring in Ontario would at least give interested readers a guide as to where to find relevant information.

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Atmospheric Environment Service
Fisheries and Environment Canada
Health and Welfare Canada
Department of National Defence

PARAMETERS MONITORED:

Joint Environmental
Observational Networks - precipitation, soil and surface layer of air for gamma, ion and isotope concentrations

NO. OF STATIONS, LOCATION:

36 in Canada

SAMPLING FREQUENCY:

At direction of agency concerned

METHOD OF MONITORING:

As appropriate

USES OF DATA:

Diverse

AVAILABILITY OF DATA:

International Atomic Energy Agency, World Meteorological Organization, Energy Research and Development Agency, Dept. of National Defence, National Health and Welfare

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ministry of Natural Resources and Ministry of the Environment

PARAMETERS MONITORED:

Biological monitoring - see below*

NO. OF STATION, LOCATION:

In vicinity of Bruce Nuclear Station

SAMPLING FREQUENCY: 1971-1974

1/y

METHOD OF MONITORING:

- both ministries did the sampling
- analysis at Radiation Protection Bureau

USES OF DATA:

- to provide pre-operational monitoring for Bruce Nuclear Station

AVAILABILITY OF DATA:

Available from MOE south-western region

* 1971 fish (bass, sunfish, perch) gross $\alpha + \beta$
1972 rabbit and rainbow trout: gross $\alpha + \beta$, Sr-89, Sr-90
1973 suckers, mooneye, bass, clams, hare
1974 suckers, channel cat, perch, clam, green algae on rocks (cladophore), drum (fish)

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Canada Center for Mineral and Energy Technology; Energy, Mines and Resources Canada

PARAMETERS MONITORED:

Radon and Radon Daughter Emissions associated with uranium mines

NO. OF STATIONS, LOCATION:

Local

SAMPLING FREQUENCY:

METHOD OF MONITORING:

Alpha particle counts by KUSNETZ method and others

USES OF DATA:

Improved measurement (and control) methods

AVAILABILITY OF DATA:

Available from Canada Center for Mineral and Energy Technology (CANMET), Energy, Mines and Resources Canada

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Canada Dept. of Fisheries and Environment

PARAMETERS MONITORED:

Water quality: H-3, Sb-125, Cs-137, Sr-90, other γ-emitters

NO. OF STATIONS, LOCATION:

Open waters of Lakes Superior, Huron, Erie and Ontario
3 stations per lake

SAMPLING FREQUENCY:

Annual

METHOD OF MONITORING:

Surface and bottom grab

USES OF DATA:

As part of IJC radioactivity surveillance program on the Great Lakes

AVAILABILITY OF DATA:

Summaries available from IJC annual report

from IJC annual
report 1976
Appendix D

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Reactor water monitoring: strontium-89, strontium-90 and cesium-137 at water intakes

NO. OF STATIONS, LOCATION:

2 Douglas Point (Lake Huron)
3 Pickering (Lake Ontario)
5 NPD and CRNL (Ottawa River)

SAMPLING FREQUENCY:

Daily Sampling for Monthly Composites

METHOD OF MONITORING:

Sampling by regional municipalities and provincial governments. Analysis by Radiation Protection Bureau

USES OF DATA:

To protect public health by monitoring radioactivity in drinking water

AVAILABILITY OF DATA:

Report by Radiation Protection Bureau and also in Great Lakes Water Quality Board Report

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Atmospheric Water Vapours from Reactor: Tritium

NO. OF STATIONS, LOCATION:

6 - Douglas Point
7 - Pickering

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

Sampling by provincial governments, utilities and private citizens. Monthly analysis of molecular sieves by Radiation Protection Bureau

USES OF DATA:

To protect public health by monitoring tritium near nuclear reactors

AVAILABILITY OF DATA:

On request from Radiation Protection Bureau

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Milk near reactors: Cesium-137
Iodine-131
Potassium

NO. OF STATIONS, LOCATION:

2 farms near Douglas Point

SAMPLING FREQUENCY:

Weekly

METHOD OF MONITORING:

Sampling by local dairy and milk producers and analysis by Radiation Protection Bureau

USES OF DATA:

To protect public health by monitoring radionuclides in milk near nuclear reactors

AVAILABILITY OF DATA:

On request from Radiation Protection Bureau

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Biota near reactors: cesium-137
strontium-90
calcium
potassium

NO. OF STATIONS, LOCATION:

NPD and CRNL
(Ottawa River)

SAMPLING FREQUENCY:

Semi-annually

METHOD OF MONITORING:

Sampling by provincial government and analysis by Radiation Protection Bureau

USES OF DATA:

To evaluate population dose from consumption of fish from water systems receiving effluent discharge from nuclear reactors

AVAILABILITY OF DATA:

On request from Radiation Protection Bureau

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Fallout - surface air, precipitation - gross beta activity

NO. OF STATIONS, LOCATION:

24 weather stations at airports across Canada

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

Sampling by Fisheries and Environment Canada
Hi-volume samplers: weekly analysis by RPB

USES OF DATA:

To evaluate the population dose from fallout radioactivity

AVAILABILITY OF DATA:

On request from Radiation Protection Bureau

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Radiation Protection Bureau
Department of National Health and Welfare

PARAMETERS MONITORED:

Fallout - milk: strontium-89, strontium-90, cesium-137, calcium and potassium, iodine-131

NO. OF STATIONS, LOCATION:

16 cities in Canada

SAMPLING FREQUENCY:

Weekly

METHOD OF MONITORING:

Composite milk samples obtained by Dept. of Agriculture
Analyzed by Radiation Protection Bureau for: Cs-137 and K-monthly composite; Sr-89, 90, Ca - quarterly composite

USES OF DATA:

To evaluate the population dose from fallout radioactivity in milk

AVAILABILITY OF DATA:

On request from Radiation Protection Bureau

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ministry of Labour

PARAMETERS MONITORED:

milk - γ scan
- I-131, H-3

NO. OF STATIONS, LOCATION:

- 9 farms in roughly 30° sectors around the Pickering area

SAMPLING FREQUENCY:

- in spring, summer and early fall: every 2 weeks
- otherwise monthly

METHOD OF MONITORING:

- samples collected by MOL, analyzed by Radiation Protection Laboratory

USES OF DATA:

As part of a contingency plan for Pickering

- provides background data so that if an upset occurs can evaluate the seriousness of any emissions

AVAILABILITY OF DATA:

- not published
- would become public in event of a contingency

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ministry of Labour

PARAMETERS MONITORED:

Water from treatment plants: γ scan
Co-60, Cs-137, H-3

NO. OF STATIONS, LOCATION:

1 in Pickering - J.S. Scott Waterworks
1 in Ajax - W.A. Parrish Waterworks
1 in Toronto - J.C. Harris Waterworks

SAMPLING FREQUENCY:

Ajax, Pickering - weekly
Toronto - once a month

METHOD OF MONITORING:

Grab samples
Plants prepare samples, MOL collects them
Analysis at Radiation Protection Laboratory, MOL

USES OF DATA:

- as part of contingency plan for Pickering - provides background data so that if upset occurs, can evaluate the seriousness of any emissions

AVAILABILITY OF DATA:

- not published
- would become public in event of a contingency

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Ministries of Environment and Labour

PARAMETERS MONITORED:

gross α, gross β, ^{226}Ra, ^{228}Ra, ^{238}U, ^{232}Th, ^{230}Th, ^{228}Th.

NO. OF STATIONS, LOCATION:

7 Serpent Harbour, North Channel

SAMPLING FREQUENCY:

2/y

METHOD OF MONITORING:

grab water sampling from Great Lakes survey vessel.

USES OF DATA:

Compliance monitoring and input to the annual assessment of Radioactivity Subcommittee, IJC

AVAILABILITY OF DATA:

Annual Reports of Radioactivity Subcommittee, IJC - Appendix D Annual Reports on Great Lakes Water Quality 1975 and 1976 published; 1977 annual report currently being prepared.

For reports contact: Secretariat Radioactivity Sub-committee, International Joint Commission
100 Ouellette Ave., Windsor, Ontario

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Ministries of Environment and Labour

PARAMETERS MONITORED:

gross α, gross β, ^{3}H, ^{60}Co, ^{137}Cs

NO. OF STATIONS, LOCATION:

8 Douglas Pt. G.S., Lake Huron
8 Bruce A G.S., Lake Huron
8 Pickering G.S., Lake Ontario

SAMPLING FREQUENCY:

3 times/y ice free season

METHOD OF MONITORING:

grab water samples taken from survey vessels - stations located off cooling water discharges of Ontario Hydro Generating Stations

USES OF DATA:

- compliance monitoring and input to the annual assessment of Radioactivity Subcommittee, IJC.

AVAILABILITY OF DATA:

- annual reports of radioactivity
- subcommittee, IJC - Appendix D.
- annual reports on Great Lakes Water Quality - 1975 and 1976 published 1977 ann. report currently being prepared.

For reports contact: Secretariat Radioactivity Subcommittee,
International Joint Commission,
100 Ouellette Ave., Windsor, Ontario.

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ministry of the Environment

PARAMETERS MONITORED:

Environmental monitoring-water: radon level in wells

NO. OF STATIONS, LOCATION:

Sampling across the province

SAMPLING FREQUENCY:

once

METHOD OF MONITORING:

samples collected by regional MOE offices

analysis by Radiation Protection Lab of MOL

USES OF DATA:

- to provide background information on radon levels in well water in Ontario

AVAILABILITY OF DATA:

- available on request from:

Water Resources Branch, MOE
135 St. Clair Ave, W.
Toronto

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE

PARAMETERS MONITORED:

Fallout monitoring - air: gross beta

NO. OF STATIONS, LOCATION:

22 cities in Ontario, 26 stations

SAMPLING FREQUENCY:

Quarterly composites

METHOD OF MONITORING:

- high volume sampler
- measurements are made after complete decay of Radon and thoron daughters

USES OF DATA:

- to estimate public dose from fallout in Ontario

AVAILABILITY OF DATA:

- published yearly in "Ontario Statistics", published by Ministry of Treasury Economics and Intergovernmental affairs
- available from MOE regional branches
- some data (from long-term programs) is coordinated by the Air Quality and Meteorology Section of the Air Resources Branch of the MOE

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE: South-west region

PARAMETERS MONITORED:

biological, water } monitoring: all water samples: undissolved solids, gross α and β, dissolved solids, gross α + β, Cs-137 tritium. See below*

NO. OF STATIONS, LOCATION:

Bruce Nuclear Power area: 8 stations each year in water near complex

SAMPLING FREQUENCY: 1970-75 inclusive

Macroinvertebrate: 3 times/y
Water and others: 1/y

METHOD OF MONITORING:

Samples collected by MOE
Analysis by Radiation Protection Lab (then in the Ministry of Health) now in Ontario Ministry of Labour

USES OF DATA:

- research
- pre-operational monitoring to provide background information

AVAILABILITY OF DATA:

Report to be published: "Levels of Radioactivity in Biota and Water in the Vicinity of Bruce Nuclear Generating Station".

* 1970 - water and crayfish (gross α + β, Co-60, Cs-137, Sr-89 Sr-90)
1971 - water and crayfish as above, also clams flesh, shell } gross α + β
1972 - water and clams (Sr-90, Sr-89 {flesh and shell}) gross α + β
1973 - water only
1974 - water and crayfish as above

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - central region

PARAMETERS MONITORED:

Ambient monitoring air: gross beta particulate

NO. OF STATIONS, LOCATION:

Pickering - 6 stations

SAMPLING FREQUENCY:

Daily

METHOD OF MONITORING:

- high volume sampling
- program conducted in cooperation with MOL

USES OF DATA:

- summaries used in MOE fallout program
- also: (1) to determine general trends
  (2) to detect any unknown emissions or plant upsets
  (3) as part of contingency plan by MOE

AVAILABILITY OF DATA:

- published summaries in "Ontario Statistics"
- available MOE Central Region
- some data (from long-term programs) is coordinated by the Air Quality and Meteorology Section of the Air Resources Branch of the MOE

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - central region

PARAMETERS MONITORED:

Ambient Monitoring - air: gross α
gross β

NO. OF STATIONS, LOCATION:

In regions of Port Hope, Port Granby

SAMPLING FREQUENCY:

Intermittent
Will become permanent if new uranium refinery is approved in Port Granby

METHOD OF MONITORING:

USES OF DATA:

- to detect any unknown emissions or upsets
- as part of contingency plan

AVAILABILITY OF DATA:

- available from MOE Central Region

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - central region

PARAMETERS MONITORED:

Effluent Monitoring: water - radium-226
Ambient Monitoring — gross α: diss, undiss
gross β: diss, undiss
uranium

NO. OF STATIONS, LOCATION:

18 - Port Hope area)
5 - Welcome area) dumpsites, effluent
12 - ENL Refinery, Port Granby) streams, Lake Ontario

SAMPLING FREQUENCY:

Lake samples - every 2 months during summer
Others as required

METHOD OF MONITORING:

Natural water grab samples
MOE staff collects samples
Analysis by MOL-Radiation Protection Laboratories

USES OF DATA:

- compliance monitoring
- to check for hazard to public health
- water data from all regions is coordinated, but not published, by the Hydrology and Monitoring Section of the Water Resources Branch
- input to the annual report of radioactivity sub-committee, IJC

AVAILABILITY OF DATA:

Data summaries available from: MOE Central Region
150 Ferrand Drive
Don Mills, Ontario
Also: Annual Reports of Radioactivity Subcommittee, IJC - Appendix D. This is an annual report on Great Lakes Water Quality - 1975 and 1976 published - 1977 report is currently being prepared
For reports contact: Secretariat, Radioactivity Subcommittee, International Joint Commission, 100 Ouelette Avenue, Windsor, Ontario.

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - central region

PARAMETERS MONITORED:

Ambient Monitoring - water: radium-226
uranium
gross α - diss, undiss
gross β - diss, undiss
(sometimes radon)

NO. OF STATIONS, LOCATION:

Cardiff Township, Bancroft area

22 stations - in or near tailings areas
- downstream from tailings areas
- community wells, Cardiff water system

SAMPLING FREQUENCY:

As required

METHOD OF MONITORING:

MOE staff does the sampling; analysis at Radiation Protection Lab (MOL)

USES OF DATA:

- to check for hazard to public health
- water data from all regions is coordinated, but not published, by the Hydrology and Monitoring Section of the Water Resources Branch

AVAILABILITY OF DATA:

- available from MOE Central Region

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - northeastern region

PARAMATERS MONITORED:

Environmental Monitoring - suspended uranium, radium gross α and β in the atmosphere and dustfall

NO. OF STATIONS, LOCATION:

9 stations around Elliot Lake measuring dustfall
4 stations around Elliot Lake measuring suspended particulate
1 at Sault Ste. Marie
1 at Sudbury

SAMPLING FREQUENCY:

dustfall sampling:	continuous, monthly composite
suspended particulate sampling:	every 6th day (weekly)

METHOD OF MONITORING:

Sampling MOE, Analysis MOL Radiation Protection Lab.

USES OF DATA:

- environmental protection

AVAILABILITY OF DATA:

- available from MOE Central Region

MONITORING INFORMATION SHEET

MONITORING AGENCY:

MOE - North-eastern region
South-western region
Central region
South-eastern region

in conjunction with Water Resources branch

PARAMETERS MONITORED:

Environmental Monitoring: Water
Solids - diss and undiss: Radium-226
Gross α - diss and undiss: Uranium-238
Gross β " "
(Cobalt 60, Cesium 137, Tritium) - At certain locations

NO. OF STATIONS, LOCATION:

Inland Watersheds Associated with the Uranium Mining and/or Processing Industry, or Nuclear Power Generation: Spanish R-7; Serpent R-74; Trent R-14; Moira R-4; Douglas Point Area R-6; Total 105

SAMPLING FREQUENCY:

Monthly in most cases
Some quarterly

METHOD OF MONITORING:

Grab samples collected regularly as part of the routine water quality network by Regional MOE Offices. Analysis by radiation protection lab of MOL administered by H & M Section Water Resources Branch, MOE.

USES OF DATA:

Determination of State; to assist in assessing need for remedial measures

Surveillance; compliance with Provincial criteria.

AVAILABILITY OF DATA:

- available on request (subject to Resource Limitations) from: R.D. Terry
  Chief, Networks
  Water Resources Branch
  or appropriate Regional Office
- data will be published commencing in 1978.

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Rio Algom and Denison Mines, Elliot Lake

PARAMETERS MONITORED:

Emission monitoring: water quality - radium and some uranium

NO. OF STATIONS, LOCATION:

- approximately 50 stations around Elliot Lake

SAMPLING FREQUENCY:

- daily to quarterly

METHOD OF MONITORING:

- both firms do their own sampling and monitoring

USES OF DATA:

- compliance monitoring

AVAILABILITY OF DATA:

- not available to the public.

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS Monitored:

Emission Monitoring - Water: tritium, gross beta-gamma

NO. OF STATIONS, LOCATION:

NPD NGS (Rolphton)
Douglas Point NGS (Tiverton)
Pickering NGS-A (Pickering)
Bruce NGS-A (Tiverton)

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

- proportional samples of cooling water streams are analyzed weekly for tritium and gross beta-gamma
- liquids that may be contaminated are collected in tanks and anlyzed for tritium and gross gamma before discharge
- gamma scans of grab samples from the liquid storage tanks are done on a monthly basis

USES OF DATA:

- to demonstrate compliance with the Atomic Energy Control Board regulatory emission limits
- trend analysis

AVAILABILITY OF DATA:

Data summaries on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Emission Monitoring - Air: tritium, noble gases, iodine-131 particulates

NO. OF STATIONS, LOCATION:

NPD NGS (Rolphton)
Douglas Point NGS (Tiverton)
Pickering NGS-A (Pickering)
Bruce NGS-A (Tiverton)

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

Tritium sampler is analyzed daily
Iodine and particulate cartridges are counted weekly
Noble gas activity is recorded daily

USES OF DATA:

To demonstrate compliance with Atomic Energy Control Board regulatory emission limits
Trend analysis

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Environmental monitoring - air: external gamma dose, tritium, radioiodine, particulates

NO. OF STATIONS, LOCATION:

4 NPD NGS (Rolphton) plus 1 reference site
4 Pickering NGS (Pickering) plus 1 reference site
8 Bruce Nuclear Power Development (Tiverton) plus 1 reference site

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

- molecular sieves (for tritium) are collected and analyzed monthly
- thermoluminescent dosimeters (external gamma dose) are collected and analyzed quarterly

USES OF DATA:

Trend analysis
Calculation of potential dose to members of the public

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Environmental monitoring - milk: radioiodine and tritium in raw milk

NO. OF STATIONS, LOCATION:

Samples are collected from up to three farms within a 10-20 kilometre radius of generating stations. Pickering NGS-A (Pickering) and Bruce Nuclear Power Development (Tiverton)

SAMPLING FREQUENCY:

Monthly, during the summer months (May-October)

METHOD OF MONITORING:

Individual milk samples are analyzed for tritium, and composite samples from each site are analyzed for iodine

USES OF DATA:

Calculation of potential dose to members of public
Trend analysis

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Environmental Monitoring - Fish: tritium and all gamma emitting nuclides

NO. OF STATIONS, LOCATION:

The vicinity of station cooling water discharges:

- Bruce NGS-A (Tiverton)
- Douglas Point NGS (Tiverton)

SAMPLING FREQUENCY:

Twice per year

METHOD OF MONITORING:

Fish flesh from available species are gamma scanned and analyzed for tritium

USES OF DATA:

Trend analysis
Calculation of potential dose to members of public

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Environmental monitoring - precipitation: tritium and gross beta activity, with occasional gamma scans

NO. OF STATIONS, LOCATION:

4 NPD NGS (Rolphton) plus 1 reference site
4 Pickering NGS (Pickering) plus 1 reference site
8 Bruce Nuclear Power Development (Tiverton) plus 1 reference site

SAMPLING FREQUENCY:

Continuous

METHOD OF MONITORING:

A composite of monthly rainfall collections is analyzed quarterly

USES OF DATA:

Trend analysis

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

MONITORING INFORMATION SHEET

MONITORING AGENCY:

Ontario Hydro

PARAMETERS MONITORED:

Environmental monitoring - drinking water:
tritium and gross beta activity

NO. OF STATIONS, LOCATION:

Sources of drinking water:

- Pickering Township water at Pickering NGS
- Bruce Nuclear Power Development Administration Building
- Bruce Nuclear Power Development Training Center Well

SAMPLING FREQUENCY:

Weekly

METHOD OF MONITORING:

Weekly samples are composited on a quarterly basis and analyzed

USES OF DATA:

Trend analysis

AVAILABILITY OF DATA:

Data summaries available on request from Ontario Hydro

APPENDIX III

(BIBLIOGRAPHY)

BIBLIOGRAPHY

All articles and books in this bibliography have been reviewed by the staff of James F. MacLaren. This bibliography is intended only to serve as a guide to further reading in those aspects of radioactivity discussed in this study. This is not an exhaustive list. Many of these articles could be classified under several different categories; however, the most suitable category for our purposes has been used.

General

"Atomic Energy Commission environmental protection conference, 2nd, Albuquerque, New Mexico, 1974." Vol. 1. Washington, D.C.: Govt. Print. Off., 1974.

Auerbach, S.I.; Dunaway, P.B.; and Dahlman, R.C. "Final report on post attack ecology." Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1973.

"Canadian Nuclear Association annual international conference, 15th, Ottawa, 1975." Vol. 4: "Economic development and nuclear policy." Toronto: Canadian Nuclear Association, 1975.

Basuk, Jack and Nichols, A. "An overview of the ionizing radiation hazard in Canada". National Science Council of Canada, Policies and Poisons Committee, 1977.

Beckmann, Peter. "The health hazards of not going nuclear." Boulder Colorado: The Golum Press, 1976.

Evans, Robley D. "The atomic nucleus." Toronto: McGraw-Hill, 1955.

Evans, Robley D. "Engineers guide to the elementary behaviour of radon daughters." "Health Physics 17 (1969): 229-252.

Kirk, William P. "Krypton 85, a review of the literature and an analysis of radiation hazards." Washington, D.C.: U.S. Environmental Protection Agency, Office of Research and Monitoring, 1972.

"Midyear topical symposium of the Health Physics Society, Northeastern New York chapter, 10th, Saratoga Springs, N.Y. 1976." Troy, N.Y: Rensselaer Polytechnic Institute, 1977.

"National Concerence on Occupational Safety and Health, 6th. Montreal, 1969." n.p., n.d. "Radiation and our environment", by A.H. Booth. reprint ed., Ottawa: Canada, Dept. of National Health and Welfare, 1969.

"New Brunswick secondary school teachers' nuclear energy seminar, Fredericton, N.B., 1973." Toronto: Canadian Nuclear Association, 1973.

Rothschild, H.C. "A criteria digest on radioactivity in the environment" National Research Council Canada No. 13566. Ottawa: National Research Council Canada, 1973.

"Seminar on the environmental impact of the disposal of radioactive material, Toronto, 1976." Edited by D.G. Andrews and J.R. Brown. Univ. of Toronto, Institute for Environmental Studies Pub. No. EE-4. Toronto: Institute for Environmental Studies, 1977.

"The great nuclear debate." "Time", December 8, 1975, pp. 48-51.

U.S. Dept. of Health, Education, and Welfare, Bureau of Radiological Health; and Training Institute, Environmental Control Administration, ed. and comp. "Radiological health handbook." Rev. ed. Rockville, Md." U.S. Dept. of Health, Education, and Welfare, Consumer Protection and Environmental Health Service, 1970.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiation Protection Activities 1975." EPA-520/7-76-004. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1976.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiation Protection Activities 1976." EPA-500/4-77-005. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1977.

Natural

Adams, John A.S., and Lowder, Wayne M. ed. "The natural radiation environment." Chicago: University of Chicago Press, 1964.

Aston, Earl A., et al. "Radiological quality of the environment." EPA-520/1-76-010. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1976.

Calabrese, Edward J. "Excessive barium and radium-226 in Illinois drinking water." "Journal of Environmental Health" 39 (March - April, 1977): 366-369.

Gesell, Thomas F., and Prichard, Howard M. "The technologically enhanced natural radiation environment." "Health Physics" 28 (April 1975): 361-366.

Jacobi, W. "Activity and potential α - energy of ^{222}radon - and - ^{220}radon - daughters in different air atmospheres." "Health Physics" 22 (May 1972): 444-450.

Krisiuk, E.M. et al. "Exposures from radiation sources of natural origin." Translated by O. Grubner. Harvard School of Public Health, 1975.

McEachern, Peter; Meyers, Willard G.; and White, Frederick A. "Uranium concentrations in surface air at rural and urban localities within New York state." "Environmental Science and Technology" 5 (August 1971) 700-703.

Moore, H.E. and Poet, S.E. "Background levels of ^{226}Ra in the lower troposphere." "Atmospheric Environment" 10 (1976): 381383.

Oakley, Donald T. "Natural radiation exposure in the United States." Doctor of Science thesis Harvard School of Public Health, 1972; reprint ed., Washington D.C.: U.S. EPA Office of Radiation Programs, 1974.

Pearson, John E. "Natural environmental radioactivity from radon 222." Public Health Service Publication No. 999-RH-26. Washington, D.C.: U.S. Dept. of Health, Education and Welfare, Public Health Service, 1967.

U.S. Environmental Protection Agency. Office of Radiation Programs. "ERAMS plutonium and uranium in air component, January - March 1974." "Radiation Data and Reports" 15 (November 1974): 719-270.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological quality of the environment." EPA-520/1-76-010. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1976.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiological quality of the environment in the United States, 1977." EPA-520/1-77-009. Sept. 1977.

U.S. National Council on Radiation Protection and Measurements. "Natural background radiation in the United States." NCRP report no. 45. Washington, D.C.: NCRP, 1975.

Building Materials

Auxier, J.A. "Respiratory Exposure in buildings due to radon progeny." "Health Physics" 31 (August 1976): 119-125.

Culot, Michael V.J.; Olson, Hilding G.; and Schiager Keith J. "Effective diffusion coefficient of radon in concrete, theory and method for field measurements." "Health Physics" 30 (March 1976): 263-270.

Culot, Michel V.J.; Schiager, Keith J.; and Olson, Hilding G. "Prediction of increased gamma fields after application of a radon barrier on concrete surfaces." "Health Physics" 30 (June 1976): 471-478.

Organization for Economic Cooperation and Development. Committee on Radiation Protection and Public Health. Ad hoc Expert Group on Radiation Protection Standards for Building Materials. "Draft radiation protection standards for building materials (2nd draft)." Paris, June 2, 1976.

Nuclear Fuel Cycle General

Atomic Energy of Canada Limited. "Nuclear Power: the Canadian issues - a submission from Atomic Energy of Canada Limited to the Royal Commission on Electric Power Planning in response to the commission's issue paper No. 1 "Nuclear Power in Ontario". AECL-5800 Chalk River, Ontario: AECL, 1977.

"Canadian Nuclear Association annual international conference, 16th, Toronto, 1976." Vol. 2: "Nuclear energy - Current evolutions." Toronto: Canadian Nuclear Association, 1976.

Canadian Nuclear Association. "Nuclear power in Canada, questions and answers." Toronto: Canadian Nuclear Association, 1975.

"Canadian Nuclear Association annual international conference, 14th, Montreal, 1974." Vol. 6: "Nuclear energy and the public." Toronto: Canadian Nuclear Association, 1974.

Canadian Nuclear Association. "The role of nuclear power in Ontario - submission to the royal commission on electric power planning." Toronto: Canadian Nuclear Association, 1976.

Cochran, Joseph A., Griffin, Jr., William R.; and Troianello, Emilio J. "Observation of airborne tritium waste discharge from a nuclear fuel reprocessing plant." EPA/ORP 73-1. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, Field Operations Division, 1973.

Cohen, Bernard L. "Environmental impacts of nuclear power due to radon emissions." "Bulletin of the Atomic Scientists." 32 (February 1976): 61-4.

Goldsmith, W.A. "Radiological aspects of inactive uranium - milling sites: an overview." "Nuclear Safety" 17 (November - December 1976): 722-732.

Hill, Philip G. "The social costs of electric power generation." Submitted to the Royal Commission on Electric Power Planning. Toronto: Ontario Government, 1977.

Kaplan, Gadi. "Bugs in the nuclear fuel cycle." "IEEE Spectrum" September 1975, pp. 56-64.

Kohler, Joel E.; Kenneke, Albert P.; and Grimes, Brian K. "Population distribution considerations in nuclear power plant siting." "Nuclear Technology" 25 (April 1975): 617-625.

Kotrappa, P., and Mayya, Y.S. "Revision of Raghavayya and Jones' data on the radon decay products in mine air." "Health Physics" 31 (October 1976): 380-382.

"Nuclear power and the environment, questions and answers." Hinsdale, Illinois: American Nuclear Society, 1976.

"Nuclear power in Canada, questions and answers." Toronto: Canadian Nuclear Association, 1975.

"Symposium on the siting of nuclear facilities, Vienna, 1974." n.p. International Atomic Energy Association, n.d. "Siting The means by which nuclear facilities are integrated into a Canadian community", by J.W. Beare and R.M. Duncan. Atomic Energy Control Board #1079. n.p., AECB, n.d.

United Nations, Scientific Committee on the Effects of Atomic Radiation. "Annex D, nuclear power production." (A/AC. 82/R.343), 14 February 1977.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Assessment of environmental radioactivity in the vicinity of Shippingport atomic power station." EPA-520/5-73-005. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1973.

U.S. Nuclear Regulatory Commission, Office of Operations Evaluation. "Summary of radioactivity released in effluents from nuclear power plants during 1973." Washington, D.C.: NRC, Office of Operational Evaluations, 1975.

U.S. NRC, "Reactor Safety Study: An assessment of accident risks in U.S. Commercial Nuclear Power Plants." U.S. Nuclear Regulatory Commission, October 1975.

Uranium Processing

Comey, David Dinsmore. "Blowing in the wind." "Bulletin of the Atomic Scientists" 32 (February 1976): 63-64.

Comey, David Dinsmore. "The legacy of uranium tailings." "Bulletin of the Atomic Scientists." 31 (September 1975): 43-5.

Fry, R.M. "Radiation hazards in uranium mining and milling." "Atomic Energy" (October 1975): 12-31.

James F. MacLaren Limited. "Industrial hygiene survey of the uranium mining and milling industry; for Canada centre for mineral and energy technology." March, 1977.

Magnv, Paul J. et al. "Iodine-129 in the environment around a nuclear fuel reprocessing plant." ORP/FOD 72-5. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, Field Operations Division, 1972.

Misaqi, F.L. "U.S. uranium mines and mills emit negligible radiation." "Mining Engineering" (August 1976): n.p.

Ramsay, William. "Radon from uranium mill tailings: a source of significant radiation hazard?" "Environmental Management" 1 (February 1976): 139-145.

Schiager, Keith J. "Analysis of radiation exposures on or near uranium mill tailings piles." "Radiation Data and Reports" 15 (July 1974): 411-425. Reprint ed., U.S. Environmental Protection Agency, Office of Radiation Programs, n.d.

Sears, M.B. et al. "Correlation of radioactive waste treatment costs and the environmental impact of waste effluents in the nuclear fuel cycle - Conversion of yellow cake to uranium hexafluoride. Part 1: The fluorination - fractionation process." ORNL/NUREG/ TM-7. Oak Ridge, Tenn.: Oak Ridge National Lab., 1977.

Snelling, Robert N. "Environmental survey of uranium mill tailings pile, Mexican Hat, Utah." "Radiological Health Data and Reports" 12 (January 1971): 17-28.

Snelling, Robert N. "Environmental survey of uranium mill tailings pile, Monument Valley, Arizona." "Radiological Health Data and Reports" 11 (October 1970): 511-517.

Tsivoglov, E.C. and O'Connell, R.L. "Nature, volume and activity of uranium mill wastes." "Radiological health and safety in mining and milling of nuclear materials, proceedings, Vienna, 1964." Vienna, IAEA, 1964.

U.S. Department of Health, Education and Welfare. Public Health Service. Division of Water Supply and Pollution Control. Radiological Pollution Activities Unit. "Process and waste characteristics at selected uranium mills." Cincinnati, Ohio: Robert A. Taft Sanitary Engineering Center, Public Health Service, 1962.

Medical

Brodsky, A. "Principles and practices for keeping occupational radiation exposures at medical institutions as low as reasonably achievable. Draft." NUREG-0267. Washington, D.C.: U.S. Nuclear Regulatory Commission, 1977.

Canada, Department of National Health and Welfare, Radiation Protection Division. "Course manual radiation hazard control in hospitals RPD-TM-1." Ottawa: Department of National Health and Welfare, 1968.

Doern, G. Bruce. "The atomic energy control board: an evaluation of regulatory and administrative processes and procedures." Ottawa: Supply and Services, Canada, 1976.

International Commission on Radiological Protection. "The handling, storage, use and disposal of unsealed radionuclides in hospitals and medical research establishments." ICRP publication 25. Annals of the ICRP, Vol. 1 No. 2. Oxford: Pergamon Press, 1977.

Johnson, Philip C. "Benefits and risks in nuclear medicine." "American Journal of Public Health" 62 (December, 1972): 1568-1572.

Lindsley, G.S. "Leakage testing of medical radium sources." "Physics in Medicine and Biology" 22 (January 1977): 64-69.

Newcombe, Howard B. "Public health aspects of radiation." Chalk River, Ont.: Atomic Energy of Canada Ltd., 1976.

Schmidt, Arthur. "Radiation hazard control in dental practice." "Ontario Dental Association Journal" 48 (June, 1971); 194-196.

Stanford Research Institute. "Survey of the use of radionuclides in medicine." Rockville, Maryland: U.S. Dept. of Health, Education and Welfare, Bureau of Radiological Health, 1970.

Statistics Canada. "Hospital Statistics, Volume 1 - Beds, Services and Personnel." 83-227 (1974)

Task Force on Short-Lived Radionuclides For Medical Applications. "The developing role of short-lived radionuclides in nuclear medicine. "Rockville, Maryland: U.S. Department of Health, Education, and Welfare, Bureau of Radiological Health, 1977.

Thompson, Carolyn H., et al. "Control of radioactive materials on the medical science campus." "Health Physics" 32 (March 1977): 179-184.

Tolan, John H. "Radioactive waste disposal in the university environment, summary of data collected in 1971." Columbia, Missouri: University of Missouri, Radiation Safety Office, 1973.

U.S. National Council on Radiation Protection and Measurements. "Radiation protection for medical and allied health personnel." NCRP report no. 48. Washington, D.C.: NCRP, 1976.

Zelac, R.E.; Bernsee, J.W.; and Han, D. "Effectiveness in a university health center setting of a commercial compactor for dry solid radioactive waste." "Health Physics" 32 (May, 1977): 452-453.

Nuclear Reactor

"Canadian Nuclear Association annual international conference, 14th, Montreal, 1974." Vol. 2: "CANDU program and research installations." Toronto: Canadian Nuclear Association, 1974.

"Canadian Nuclear Association annual international conference, 16th, Toronto, 1976." Vol. 6: "Heavy water reactors." Toronto: Canadian Nuclear Association, 1976.

MacLaren Atlantic Limited and Dilworth, Secord, and Meagher and Associates Limited. "Preliminary environmental impact statement - Lepreau nuclear generating station" Moncton: n.p., 1974.

McIntyre, Hugh C. "Natural-uranium heavy-water reactors." "Scientific American" 233 (October 1975): 17-27.

Inadvertent

Babu, Suresh P., ed. "Trace elements in fuel." Advances in Chemistry Series 141. Washington, D.C.: American Chemical Society, 1975.

Barber, D.E., and Giorgio, H.R. "Gamma-ray activity in bituminous, subbituminous and lignite coals." "Health Physics" 32 (February 1977): 83-88.

Bayliss, R.J. and White, H.M. "A study of the radium alpha-activity of coal, ash and particulate emission at a Sydney power station." "Air and Water Pollution" 10 (1966): 813-819.

"Canadian mines handbook 1977-78." Toronto: Northern Mines Press Limited, 1977.

Cuffe, Stanley J. and Gerstle, Richard W. "Emissions from coal-fired power plants: a comprehensive summary." Environmental Health Series. Durham, North Carolina: U.S. Dept. of Health, Education, and Welfare Public Health Service, National Air-Pollution Control Administration, 1967.

Curtis, H.W. "Trends in European irradiated fuel transport." "Nuclear Engineering International" 22 (July 1977): 57-59.

Duggan, M.J.; Soilleux, P.J.; Strong, J.C.; and Howell, D.M. "The exposure of United Kingdom miners to radon." "British Journal of Industrial Medicine" 27 (1970): 106-109.

Glasgow, G.P., and Luszczynski, K. "Radiation exposure of airport workers at the St. Louis international airport." Abstract. "Physics in Medicine and Biology" 22 (March 1977): 600.

Guimond, Richard J., and Windham, Samuel T. "Radioactivity distribution in phosphate products, byproducts, effluents, and wastes." ORP/CSD-75-3. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, Criteria and Standards Division, 1975.

Hedlin Menzies and Associates Limited. "An assessment of the farm supply industries and their impact on farming." Toronto: Hedlin Menzies and Associates Limited, 1968.

Hill, Philip G. "The social costs of electric power generation." Submitted to the Royal Commission on Electric Power Planning. Toronto: Ontario Govt., 1977.

Jefferson, Robert M. "Cask demolishes train superstructure sustains minor damage." "Nuclear Engineering International" 22 (July 1977): 59-61.

Koepke, W.E. "Fertilizers and fertilizer minerals in Canada." Ottawa: Department of Energy, Mines and Resources, Mineral Resources Branch, 1971.

Lave, L.B., and Freeburg, L.C. "Health effects of electricity generation from coal, oil, and nuclear fuel." "Nuclear Safety" 14 (September - October 1973): 409-428.

Montgomery, W.J. et al. "Chemical analyses of the ash of Canadian coals." Mines Branch Information Circular IC 248. Ottawa: Dept. of Energy, Mines and Resources, Mines Branch, 1970.

Natusch, D.F.S.; Wallace, J.R.; and Evans, C.A. "Toxic trace elements: preferential concentration in respirable particles." "Science" 183 (January 1974): 202-204.

Newfoundland. Royal Commission Respecting Radiation, compensation and Safety at the Fluorspar Mines, St. Lawrence, Nfld. "Report" n.p., 1969.

Nuclear Safety Staff. "Transport of radioactive materials in the United States." "Nuclear Safety" 18 (May - June 1977): 291-297.

Ogden, J.L. "A method for measuring the working-level values of mixed radon and thoron daughters in coalmine air." "Annals of Occupational Hygiene" 17 (1974): 23-24.

O'Gorman, J.V. and Walker Jr., P.L. "Mineral matter and trace elements in U.S. coals." Research and Development Report No. 61, Interim Report No. 2. University Park, Pennsylvania: Pennsylvania State University, Coal Research Section, College of Earth and Mineral Sciences, 1972.

Ontario Dept. of Agriculture and Food, The Farm Economics, Cooperatives and Statistics Branch. "The fertilizer industry in Ontario." Toronto: The Special Committee on Farm Income in Ontario, 1970.

"Ontario Mineral Review 1975." Toronto: Ministry of Natural Resources, 1976.

Rabbani, B., et al. "Radiation exposure of airline cargo personnel from radiopharmaceuticals." Abstract. "Physics in Medicine and Biology" 22 (March 1977): 601.

Roberts, Alan I. "MTB proposed requirements for transportation of radioactive materials by aircraft." "Chemical Regulation Reporter" 1 (July 1977): 707-710.

Rock, R.L. et al. "Evaluation of radioactive aerosols in United States underground coal mines." Informational report 1025. Washington, D.C.: U.S. Dept. of the Interior, Mining enforcement and safety administration, 1975.

Sagan, L.A. "Health costs associated with the mining, transport and combustion of coal in the steamelectric industry." "Nature" 250 (July 1974): 107-111.

Sciocchetti, G. "Survey of airborne radioactivity in Italian mines." n.p., Dipartimento Radiazioni, CSN Casaccia, CNEN, Italy, n.d.

Sniks, Jan Olaf and Ehdwall, Hans. "Supervision of radon daughter exposure in mines in Sweden." "Specialist meeting on personal dosimetry and area monitoring suitable for radon and daughter products, Elliot Lake, Ontario, 1976." n.p. OECD, Nuclear Energy Agency, 1976.

Statistics Canada. "Fertilizer Trade" 46-207 (1976): 6.

Strong, J.C.; Laidlaw, A.J.; and O'Riordan, M.C. "Radon and its daughters in various British mines." Harwell, Britain: National Radiological Protection Board, 1975.

"Supporting Data for Amendment to Source Material Licence Sub-1010 to Permit the Commercial Disposal of Barium Treated Solvent Extraction Raffinate." Kerr-McGee Nuclear Corporation, Oklahoma, 1975.

U.S. Environmental Protection Agency. Office of Radiation Programs. "Considerations for control of radiation exposures to personnel from shipments of radioactive materials on passenger aircraft." Washington, D.C.: U.S. EPA Office of Radiation Programs, 1974.

U.S. Environmental Protection Agency. Office of Radiation Programs. "Transportation accident risks in the nuclear power industry 1975-2020." Washington, D.C.: U.S. EPA Office of Radiation Programs, 1975.

Walsh, M.L. "An estimate of the dose resulting from a spill of tritrated heavy water during transportation." Toronto: Ontario Hydro, Health Physics Department, 1970.

Windham, Sam; Partridge, Jennings and Horton, Thomas. "Radiation dose estimates to phosphate industry personnel." Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1976.

Zubovic, Peter et al. "Distribution of minor elements in coal beds of the eastern interior region." Geological Survey Bulletin 1117-B. Washington: U.S. Dept. of the Interior, Government Printing Office, 1964.

Zubovic, Peter et al. "Distribution of minor elements in some coals in the western and southwestern regions of the interior coal province." Geological Survey Bulletin 1117-D. Washington: U.S. Dept of the Interior, Government Printing Office, 1967.

Zubovic, Peter; Stadnichenko, Taisia; and Sheffey, Nola B. "Distribution of minor elements in coals of the appalachian region." Geological Survey Bulletin 1117-C. Washington: U.S. Dept. of the Interior U.S. Government Printing Office, 1966.

Industrial and Commercial

Bowen, H.J.M. "Chemical applications of radioisotopes." London: Methuen and Co. Ltd., 1969.

Cameron, J.F. and Clayton, C.G. "Radioisotope instruments, Part I." International Series of Monographs in Nuclear Energy Vol. 107. Toronto: Pergamon Press, 1971.

Darley, J.J., and Ezoe, H. "Potential hazards of uranium and its compounds in electron microscopy: a brief review." "Journal of Microscopy" 106 (1976): 85-86.

"Development of depleted uranium catalysts, for destruction of air pollutants in automobile exhaust." PB-171-980. Washington, D.C.: Bureau of Mines, 1961.

International Atomic Energy Agency. "Commercial portable gauges for radiometric determination of the density and moisture content of building materials: a comparative study." Technical Report Series No. 130. Vienna: IAEA, 1971.

International Atomic Energy Agency. "Neutron moisture gauges." Technical Report Series No. 112. Vienna: IAEA, 1970.

International Atomic Energy Agency. "Radioisotope x-ray fluorescence spectrometry." Technical Report Series No. 115. Vienna: IAEA, 1970.

Johnson, J.E. "Smoke detectors containing radioactive materials." Cedar Knolls, N.J.: Pyrotronics, n.d.

"Kirk-Othmer Encyclopedia of Chemical Technology", 2nd ed. S.V. Radioisotopes."

"Kirk-Othmer Encyclopedia of Chemical Technology", 2nd ed. S.V. "Thorium and thorium compounds."

Kosmoski, Alfred. "Radionuclides in scientific and technical fields." "Wasser Luft und Betrieb" 13 (December 1969): 469-471.

Kotrappa, P.; Bhanti, D.P.; Menon, V.B.; Dhandayutham, R.; Gohel, C.O.; and Nambian, P.P.V.J. "Assessment of airborne hazards in the thorium processing industry." "American Industrial Hygiene Association Journal" 37 (November 1976): 613-616.

McElheny, Victor K. "Technology: Sewage disinfected by electron-beam bombardment." "New York Times", 3 November, 1976.

Ogden, T.L. "Radon and thoron working levels from ordinary industrial-hygiene dust samples." "Annals of Occupational Hygiene" 20 (1977): 49-53.

Oziewicz, Stan. "Radiation emission questioned, smoke-detection units less hazardous than color TVs expert says." "Globe and Mail", 19 June, 1976.

Pyrotronics Canada Ltd. "Pyrotronics ionization detectors are safe and save lives." "News Release", N-4-76, 1976.

Roberts, K.J., and Vajdic, A.H. "Alternative methods of disinfection: how effective." "Water and Sewage Works" (September, 1974): 72-75.

U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The effects on populations of exposure to low levels of ionizing radiation." Washington, D.C.: National Academy of Science, 1972.

U.S. Atomic Energy Commission. "Radioisotopes in sciences and industry, special report." Washington, D.C.: U.S. AEC, 1960.

U.S. Dept. of Commerce. "News" FP76-25, November 8, 1976.

Uto, Akio. "Method and apparatus for increasing output of car engine and purifying exhaust gas." U.S. patent 3.678.908, July 25, 1972.

Waste Management

Aikin, A.M.; Harrison, J.M. and Hare F.K. "The management of Canada's nuclear wastes." Energy, Mines and Resources Canada, Report EP 77-6. Ottawa: Supply and Services, 1977.

Barnes, R.W. and Mayman, S.A. "The Canadian program for management of spent fuel and high level wastes." "Joint topical meeting on commercial nuclear fuel technology today, proceedings, Toronto, 1975." n.p., n.d.

Battelle, Pacific Northwest Laboratories. "Alternatives for managing wastes from reactors and post-fission operations in the LWR fuel cycle." Vol. 1. Washington, D.C.: U.S. Energy Research and Development Administration, 1976.

Coleman, R.L.; and Wallace, B.P. "Tailing disposal in Canada." "Canadian Institute of Mining and Metallurgy, Special Volume." 16 (1977): 13-20.

Didyk, J.P.; Nurmsoo, U. and Power, J.C. "Regulating the management of radioactive waste in Canada." Atomic Energy Control Board #1081. n.p., AECB, 1975.

"Disposal of radioactive wastes into sea, oceans and surface waters, proceedings of the symposium, Vienna, 1966." Vienna: International Atomic Energy Agency, 1966.

Dyne, Peter J. "Managing nuclear wastes". Ottawa: Atomic Energy of Canada Ltd., n.d.

"Management of low- and intermediate-level radioactive wastes, proceedings of a symposium, Aix-en-Provence, 1970." Vienna: International Atomic Energy Agency, 1970.

Mawson, C.A. "Nuclear waste management in Canada." "Journal Water Pollution Control Federation" 35 (August 1963): 1055-1065.

Morrison, J.A. "AECL experience in managing radioactive wastes from Canadian nuclear reactors." Chalk River, Ontario: Chalk River Nuclear Laboratories, 1974.

Morrison, J.A. "The CRNL development program for the management of low and medium level radioactive wastes." Notes from a slide presentation, June, 1975.

Morrison, J.A. "The management of radioactive wastes resulting from emergency situations on land and sea." "Atomic Energy Review" 13 (1975): 413-421. Reprint edition. Vienna: International Atomic Energy Agency, 1975.

Mullarkey, J.B. et al. "A survey and evaluation of handling and disposing of solid low-level nuclear fuel cycle wastes." Washington, D.C." Atomic Industrial Forum, Inc., 1976.

"Proceedings of a symposium on the management of radioactive wastes from the nuclear fuel cycle, Vienna, 1976." 2 vols. Vienna: International Atomic Energy Agency, 1976.

Schneider, K.J., and Platt, A.M. ed. "High-level radioactive waste management alternatives." Richland, Washington: Battelle Pacific Northwest Laboratories, 1974.

Scott, J.S. and Bragg K., ed. "Mine and mill wastewater treatment." Water Pollution Control Directorate EPS 3-WP-75-5. Ottawa: Information Canada, 1975.

Slansky, Cyril M.; Peterson, Henry K.; and Johnson, Vernon G "Nuclear power growth spurs interest in fuel plant wastes." "Environmental Science and Technology" 3 (May 1969): 446-451.

Tammemagi, H.Y. "Geological disposal of radioactive wastes - the Canadian development program." Pinawa, Manitoba: Atomic Energy of Canada Limited, Whiteshell Nuclear Research Establishment, 1976.

Tammemagi, H.Y.; Gale, J.E.; and Sanford, B.V. "Underground disposal of Canada's nuclear waste." "Geoscience Canada" 4 (1977): 71-76.

Vivyurka, A.J. "Rehabilitation of uranium mines tailings areas." "Canadian Mining Journal" (June 1975): 44-45.

Ranger Uranium Environmental Inquiry. "Second report." Canberra, Australia: Australian Government Publishing Service, 1977.

Tennessee Valley Authority and U.S. Dept. of the Interior. "Draft environmental statement, Dalton Pass uranium mine." Washington, D.C.: Council on Environmental Quality, 1977.

U.S. Atomic Energy Commission, Directorate of Licensing. "Final detailed statement on the environmental considerations related to the proposed issuance of a license to Exxon Company, U.S.A. for the Highland Uranium mill." Washington, D.C.: U.S. Atomic Energy Commission, 1973.

United Nuclear Corporation, Mining and Milling Division. "Applicant's environmental report on the Morton Ranch, Wyoming, uranium mill." 2 vols. n.p., United Nuclear Corp. 1976.

U.S. Nuclear Regulatory Commission; U.S. Dept. of the Interior, Geological Survey; and U.S. Dept. of Agriculture, Forest Service. "Draft environmental statement related to the Rocky Mountain Energy Company's Bear Creek Project (Converse County, Wyoming)." NUREG-0129. Washington, D.C.: U.S. Nuclear Regulatory Commission, Office of Nuclear Material Safety and Safeguards, 1977.

Pollution Controls

American Conference of Governmental Industrial Hygienists, Committee on Industrial Ventilation. "Industrial ventilation, a manual of recommended practice." 14th ed. Lansing, Michigan: American Conference of Governmental Industrial Hygienists, 1976.

Arthur D. Little Inc. "Advanced techniques for radon gas removal." U.S. Bureau of Mines Open File Report 60-75. Cambridge, Mass.: Arthur D. Little, 1975.

Banerjee, S. "Reactor Safety, waste management, and environmental considerations." Dept. of Engineering Physics, McMaster University, Hamilton.

Blanco, R.E. "Controlling the radiological impact in the nuclear fuel cycle: A cost/beneft analysis." Oak Ridge, Tennessee: Oak Ridge National Lab., 1976.

Burchsted, C.A.,; Kahn, J.E.; and Fuller, A.B. "Nuclear air cleaning handbook." Oak Ridge, Tennessee: Oak Ridge National Laboratory, 1976.

Caplin, Jerrold L., et al. "Manual of respiratory protection against airborne radioactive materials." Washington D.C.: U.S. Nuclear Regulatory Commission, Office of Standards Development, 1976.

"Canadian Nuclear Association annual international conference, 16th, Toronto, 1976." Vol. 8: "Scientific session - Control of reactor radiation fields." Toronto: Canadian Nuclear Association, 1976.

Gray, D.H. and Chakravatti, J.L. "Improving the ventilation system and the control of mining environment at Denison Mines Ltd., Elliot Lake, Ontario. Toronto: Mines Accident Prevention Association of Ontario, 1976.

Hoenig, Stuart A; Russ, Charles F. and Bidwell, Joseph B. "Application of electrostatic fog techniques to the control of respiratory particulates." Toronto: Mines Accident Prevention Association of Ontario, 1976.

"Manual on radiological safety in uranium and thorium mines and mills." Safety Series No. 43. Vienna: International Atomic Energy Agency, 1976.

"Proceedings of a symposium on operating and developmental experience in the treatment of airborne radioactive wastes, New York, 1968." Vienna: International Atomic Energy Agency, 1968.

"Radiation protection in mining and milling of uranium and thorium." Proceedings of a symposium organized by the International Atomic Energy Commission, in cooperation with the World Health Organization and the International Atomic Energy Agency, Bordeaux, France, 1974. Occupational Safety and Health Series 32. Geneva: International Labour Office, 1976.

"Radioactivity management and nuclear safety." "IAEA Bulletin" 19 (1977): 21-25.

Environment - Transport and Fate

Allied Chemical Corporation. "Environmental information, Metropolis Works, uranium hexafluoride facility, Metropolis, Illinois." n.p. U.S. Nuclear Regulatory Commission, 1975.

Berkowitz, David H. and Squires, Arthur M., ed. "Power generation and environmental change." Cambridge Mass.: Massachusetts Institute of Technology, 1971.

Blaylock, B.G. "Effects on aquatic biota of radioactive effluents from nuclear power stations." Oak Ridge, Tennessee" Oak Ridge National Laboratory, Environmental Sciences Division, 1972.

Chapman, William H.; Fisher, H. Leonard; and Pratt, Michael W. "Concentration factors of chemical elements in edible aquatic organisms." Livermore, California: Lawrence Radiation Laboratory, University of California, 1968.

Eichholz, Geoffrey G. "Environmental aspects of nuclear power." Ann Arbor, Michigan: Ann Arbor Science Publishers Inc., 1976.

Environmental Analysts, Inc. "Standard methodology for calculating radiation dose to lower form biota." Washington, D.C.: Atomic Industrial Forum, Inc., 1975.

"Environmental behaviour of radionuclides released in the nuclear industry, proceedings, Aix-en-Provence, 1973." Vienna: International Atomic Energy Agency, 1973.

"Environmental behaviour of radionuclides released in the nuclear industry." Vienna: International Atomic Energy Agency, 1973. "The environmental capacity of freshwaters for waste radionuclides", by I.L. Ophel. reprint ed., Chalk River, Ont.: Atomic Energy of Canada Ltd., n.d.

Evans, E.J. "Chemical investigations of the movement of fission products in soil." AECL No. 667. Chalk River, Ontario: Atomic Energy of Canada Limited, 1958.

Food and Agriculture Organization of the United Nations. "Radioactive materials in food and agriculture." Rome: F.A.O., 1960.

Gammage, R.B., and Cheka, J.S. "A preliminary assessment of $^{239,240}Pu$ concentrations in a stream near Argonne National Laboratory." "Health Physics" 32 (March 1977): 195-198.

Garner, R.J. "Transfer of radioactive materials from the terrestrial environment to animals and man." Cleveland, Ohio: Chemical Rubber Company Press, 1972.

Honstead, John F. and Essig, Thomas H. "Evaluation of environmental

factors affecting population exposure." "Southern conference on environmental radiation protection from nuclear power plants proceedings 1971." n.p., U.S. Environmental Protection Agency, 1972.

International Atomic Energy Agency. "Effects of ionizing radiation on aquatic organisms and ecosystems." Technical reports series no. 172. Vienna: IAEA, 1976.

"International Symposium on Radioecology Applied to the Protection of Man and his Environment, Rome, 1971." n.p., n.d. "Strontium concentration factors in biota and bottom sediments of a freshwater lake", by I.L. Ophel, C.D. Fraser and J.M. Judd. Reprint ed., AECL-4475. Chalk River, Ont.: Atomic Energy of Canada Ltd., n.d.

Kaufmann, Robert F.; Eadie, Gregory G.; and Russell, Charles R. "Effects of uranium mining and milling on groundwater in the Grants mineral belt, New Mexico." "Groundwater" (September - October 1976): 296-308.

Kerr-McGee Corporation "Environmental report Sequoyah facility Kerr-McGee Corporation supplemental." n.p. U.S. Atomic Energy Corporation, 1972.

Magno, Paul J., et al. "Studies of ingestion dose pathways from the nuclear fuel services fuel reprocessing plant." EPA-520/3-74-001. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1974.

Mayer, Ramona A., et al., comp. "Bioenvironmental effects associated with nuclear power plants; a selected bibliography." Columbus, Ohio: Battelle, Columbus Laboratories, 1972.

Megumi, Kazuko and Mamuro, Tetsuo. "Radon and thoron exhalation from the ground." "Journal of Geophysical Research" 78 (April 1973): 1804-1808.

National Symposium on Radioecology, 3rd, 1971. "Radionuclides in ecosystems." n.p., n.d. "The fate of cobalt-60 in a natural freshwater ecosystem", by I.L. Ophel and C.D. Fraser. Reprint ed., AECL-4627. Chalk River, Ont.: Atomic Energy of Canada Ltd., n.d.

Newton, J.D. "On the dispersion of fission products by groundwater." AECL no. 909. Chalk River, Ontario: Atomic Energy of Canada Limited, 1959.

Ophel, I.L., and Fraser, C.D. "Calcium and strontium discrimination by aquatic plants." AECL-3539. Chalk River, Ontario: Atomic Energy of Canada Limited, 1969. Reprint ed., Ecology 51 (Early spring, 1970): 324-327.

Ophel, I.L. "The environmental capacity of freshwaters for waste radionuclides." Reprint from: "Environmental behaviour of radionuclides

released in the nuclear industry." Vienna: International Atomic Energy Agency, 1973.

Parthasarathy, K.S. "Decay products of ^{222}Rn in the living environment." "Health Physics" 31 (August 1976): 187-188.

"Radioactive contamination of the marine environment proceedings of a symposium, Seattle, Washington, 1972." Vienna: International Atomic Energy Agency, 1973.

"Radioactivity in the marine environment." Washington, D.C.: National Academy of Sciences, 1971. Chapt. 10: "Evaluation of human radiation exposure", by F. Foster, I.L. Ophel and A. Preston. Reprint ed. Atomic Energy Control Ltd. #4091. Chalk River, Ont.: Atomic Energy of Canada Ltd., n.d.

"Radioecological Concentration Processes, proceedings of an international symposium, Stockholm, 1966." Oxford: Pergamon Press, 1966. "Experimental studies of radiostrontium accumulation by freshwater fish from food and water", by I.L. Ophel and J.M. Judd, reprint ed., AECL-2494. Chalk River, Ont.: Atomic Energy of Canada Ltd., n.d.

Soldat, J.K. "Aquatic Exposure Pathways - Potential Exposure to Man from Environmental Transport of Waste Radionuclides." BNWL-SA-5843. Battelle, Pacific Northwest Laboratory, Richland, Washington 99352, September 1976.

Stewart, C.G. "Perspectives in the field of radiation protection." "Seminar on the environmental impact of the disposal of radioactive material, Toronto, 1976." Pub. No. EE-4. Toronto: University of Toronto, Inst. for Environmental Studies, 1977.

"Transuranium nuclides in the environment, proceedings of the symposium, San Francisco, 1975." Vienna, International Atomic Energy Agency, 1976.

U.S. Environmental Protection Agency, Office of Radiation Programs, Criteria and Standards Division. "Environmental radiation dose commitment: An application to the nuclear power industry." EPA-520/4-73-002. Washington, D.C.: U.S. EPA Office of Radiation Programs, 1974.

U.S. National Research Council. Committee on Oceanography. Panel on Radioactivity in the Marine Environment. "Radioactivity in the marine environment." Washington, D.C.: U.S. National Academy of Sciences, 1971.

Vorklovskaya, I.N.; Varilov, P.P.; and Maslov, V.I. "Distribution and redistribution of uranium, radium, and thorium in natural biogeocenoses." n.p., 1974.

Health Effects - General

Anderson, Terence W. "Radiation exposures of Hanford workers: A critique of the Mancuso, Stewart and Kneale report." Submitted to Health Physics, February 1978.

Archer, Victor E. "Occupational exposure to radiation as a cancer hazard." "Cancer" 39 (April 1977): 1802-1806.

Archer, Victor E.; Gilliam, J. Dean; and Wagoner, Joseph K. "Respiratory disease mortality among uranium miners." "Annals of the New York Academy of Sciences" 271 (May 1976): 280-293.

Archer, Victor E. et al. "Respiratory disease mortality among uranium miners as related to height, radiation, smoking and latent period." Salt Lake City, Utah: U.S. National Institute for Occupational Safety and Health, 1975.

Berlin, Nathaniel I., and Wasserman, Louis R. "The association between systematically administered radioisotopes and subsequent malignant diseases." "Cancer" 37 (Feb., 1976): 1097-1101. Note: Supplement.

Blair, H.A. "Dose-time relations for induction of lung cancer in uranium miners." U.S. Atomic Energy Commission report No. UR-49-1065. Rochester, N.Y.: University of Rochester, National Institute of Environmental Health Sciences, n.d.

Brown, J. Martin. "Linearity vs. non-linearity of dose response for radiation carcinogenesis." "Health Physics" 31 (September 1976): 237-245.

Budd, Roger A. "Summary of selected experimental evidence for biological effects in mammalian tissues following low level X or gamma irradiation." n.p., 1976.

Carver, J.S. "Radiation exposure and the woman worker: Biological and legal parameters." Oak Ridge, Tennessee: Oak Ridge National Laboratory, Health Physics Division, n.d.

"Conference on the estimation of low-level radiation effects in human populations, Argonne, Illinois, 1970." Argonne, Illinois: Argonne National Laboratory, 1971.

"Conference on occupational health experience with uranium, Arlington, Virginia, 1975." Washington, D.C.: U.S. Energy Research and Development Administration, 1975.

Cosandey, Maurice, and Wenger, Pierre. "Retention and excretion of radium-226 and strontium-90 in two doubly contaminated persons." "Health Physics" 31 (September 1976): 225-229.

Desrosiers, Arthur E. "Alpha particle dose to respiratory airway epithelium." "Health Physics" 32 (March 1977): 192-195.

DeVilliers, A.J. et al. "Mortality experience of the Community and of the fluorspar mining employees at St. Lawrence, Newfoundland." n.p., n.d.

Dudley, Robert A. "Natural and artificial radiation background of man." reprinted from, "Low Level Irradiation" Washington, D.C.: American Association for the Advancement of Science, 1959.

Duggan, M.J. "Some aspects of the hazard from airborne thoron and its daughter products." "Health Physics" 24 (March 1973): 301-310.

Evans, Robley D. "Radium in man." "Health Physics" 27 (November 1974): 497-510.

"Environmental mutagenic hazards: mutagenicity screening is now both feasible and necessary for chemicals entering the environment." "Science" 187 (February 1975): 503-514.

Flowers, Earl S. "Proposal: a nonzero approach to environmental limits for carcinogens." "Occupational Health and Safety" (May-June 1977): 35-39.

Franca, E. Penna. "Review of Brazilian investigations in areas of high natural radioactivity. Part II: internal exposure and cytogenic survey." n.p., n.d.

George, A.C., and Breslin, A.J. "Deposition of natural radon daughters in human subjects." "Health Physics" 13 (1967): 375-378.

Gotchy, R.L. "Health effects attributable to coal and nuclear fuel cycle alternatives, draft." NUREG-0332 Washington, D.C.: U.S. Nuclear Regulatory Commission, Division of Site Safety and Environmental Analysis, 1977.

Haley, Thomas J. "Pharmacology and toxicology of the rare earth elements." "Journal of Pharmaceutical Sciences" 54 (May 1965): 663-670.

Hamrick, Philip E., and Walsh, Phillip J. "Environmental radiation and the lung." "Environmental Health Perspectives" 9 (December 1974): 33-52.

Haque, A.K.M.M., and Collinson, A.J.L. "Radiation dose to the respiratory system due to radon and its daughter products." "Health Physics" 13 (1967): 431-443.

Hermann, K., and Kraus, W. "Relations between radiation risks and radiation protection measuring techniques." Translated by The Ralph McElroy Company, Austin, Texas. Livermore, California: Lawrence Livermore Laboratory, 1976.

"High cancer rate found in workers exposed to 'safe' radiation levels." "Globe and Mail", 1 December 1977.

Hutchinson, George B. "Late neoplastic changes following medical irradiation." "Cancer" 32 (February 1976): 1102-1107. Note: Supplement

Jacobi, W. "Relations between the inhaled potential α - energy of ^{222}Rn -and ^{220}Rn - daughters and the absorbed α-energy in the bronchial and pulmonary region." "Health Physics" 23 (July 1972): 3-11.

Lee, K.H.; Kagan, A.R.; and Norman, A. "Analysis of dose, dose-rate and treatment time in the production of injuries by radium treatment for cancer of the uterine cervix." "British Journal of Radiology" 49 (May 1976): 430-440.

Mancuso, Thomas F.; Stewart, Alice and Kneale, George. "Radiation exposures of Hanford workers dying from cancer and other causes." "Mid-year symposium of the Health Physics Society, Saratoga Springs, N.Y., 1976" n.p., n.d.; revised ed., draft, n.p., March 1977.

Mancuso, T.F.; Stewart, A. and Kneale, G. "Radiation exposures of Hanford workers dying from cancer and other causes." "Health Physics" 33 (November 1977): 369-385.

Manocha, K.K., and Mohindra, R.K. "Estimate of natural internal radiation dose to man." "Health Physics" 30 (June 1976): 485-487.

Marks, Sidney and Gilbert, Ethel S. "Comments on paper: Radiation exposures to Hanford workers dying of various causes' authored by Mancuso, Stewart and Kneale." n.p., Battelle Northwest Laboratory, n.d.

Marks, Sidney and Gilbert, Ethel S. "Comments on paper: Radiation exposures of Hanford workers dying of various causes." "Midyear Symposium of the Health Physics Society, 10th, Saratoga Springs, N.Y., 1976." n.p., n.d.

Martin, D., and Jacobi, W. "Diffusion deposition of small-sized particles in the bronchial tree." "Health Physics" 23 (July 1972): 23-29.

Mason, Thomas J.; Fraumeni, Joseph F.; and McKay, Frank W. "Uranium mill tailings and cancer mortality in Colorado." "Journal of the National Cancer Institute" 49 (September 1972): 661-664.

Megumi, Kazuko, and Mamuro, Tetsuo. "Radon and thoron exhalation from the ground" "Journal of Geophysical Research" 78 (April, 1973): 1804-1808.

Muller, J. and Wheeler, W.C. "Causes of death in Ontario uranium miners." "International symposium on radiation protection in mining and milling of uranium and thorium, Bordeaux, France, 1974." Geneva, International Labour Office, 1976.

O'Brien, Keran, and Sanna, Robert. "The distribution of absorbed dose-rates in humans from exposure to environmental gamma rays." "Health Physics" 30 (January 1976): 71-78.

Okada, Shigefumi et al ed. "A review of thirty years study of Hiroshima and Nagasaki atomic bomb survivors." "Journal of Radiation Research" (supplement, 1975).

Ontario Ministry of Health. "Survey of certain conditions of the respiratory organs among persons employed underground and in surface crushers and mills of two operating uranium mills at Elliot Lake, Ontario, February 17 - March 30, 1974." Toronto: Ontario Ministry of Health, 1975.

Pochin, E.E. "Problems involved in detecting increased malignancy rates in areas of high natural radiation background." "Health Physics" 31 (August 1976): 148-151.

Pohl, Egon, and PohlRuling, Johanna. "Dose Calculation due to the inhalation of ^{222}Rn, ^{220}Rn and their daughters." "Health Physics" 32 (June 1977): 552-555.

Pohl, Robert O. "Health effects of radon-222 from uranium mining." "Search" 7 (August 1976): 345-54.

Reissland, T.A.; and Dolphin, G.W. "Radiation exposures of Hanford workers dying from cancer and other causes." U.K. National Radiation Protection Board, 1977.

Rock, Robert L. "Measurement of employees' individual cumulative exposures to radon daughters as practiced in the United States" Elliot Lake, Ontario, Nuclear Energy Agency Meeting, October 4-8, 1976.

Science Council of Canada. "Policies and Poisons - The containment of long-term hazards to human health in the environment and in the workplace." Report No. 28. Ottawa, Ontario: Supply and Services, 1977.

Scott, L.M. et al. "Mortality experience of uranium and non-uranium workers." "Health Physics" 23 (October 1972): 555-557.

Sevc, J.; Kunz, E.; and Placek, V. "Lung cancer in uranium miners and long-term exposure to radon daughter products." "Health Physics" 30 (June 1976): 433-437.

Shleien, B. "An estimate of radiation doses received by individuals living in the vicinity of a nuclear fuel reprocessing plant in 1968." Rockville, Maryland: U.S. Department of Health, Education, and Welfare, Public Health Service, Environmental Health Service, 1970.

Shleien, Bernard; Wall, Mary A.; and Lutz, David. "Estimation of radiation doses to the respiratory tract from inhalation of airborne radioactivity." "Environmental Science and Technology" 2 (June 1968): 438-443.

Spiers, F.W., and Vaughan, Janet. "Hazards of plutonium with special reference to the skeleton." "Nature" 259 (February 1976): 531-534.

Stewart, Alice. "An epidemiologist takes a look at radiation risks." Rockville, Maryland: Food and Drug Administration, Bureau of Radiological Health, 1973.

Stewart, A.M. "Cancer as a cause of abortions and still-births: the effect of these early deaths on the recognition of radiogenic leukaemias." "British Journal of Cancer" 27 (1973): 465-472.

Stewart, C.G. "An estimate of the potential hazard associated with exposure at the rate of 4.0 working level months per year from age 20 to age 60 years." Chalk River, Ontario: Chalk River Nuclear Laboratories, 1976.

Stewart, C.G. "An estimation of the potential risk of lung cancer associated with continued exposure to low levels of airborne Rn^{222} and its short-lived daughters." Chalk River, Ontario: Chalk River Nuclear Laboratories, 1976.

Thorne, M.C. "Aspects of the dosimetry of Alpha-emitting radionuclides in bone with particular emphasis ^{226}Ra and ^{239}Pu." "Physics in Medicine and biology" 22 (January 1977): 36-46.

Thorne, M.C. and Vennart, J. "The toxicity of ^{90}Sr, ^{226}Ra and ^{239}Pu." "Nature" 263 (October 1976): 555-558.

U.S. Advisory Committee on the Biological Effects of Ionizing Radiations. "The effects on populations of exposure to low levels of ionizing radiation." Washington, D.C.: National Academy of Sciences, 1972.

U.S. Environmental Protection Agency. Office of Radiation Programs. "Calculations of doses, population doses, and potential health effects due to atmospheric releases of radionuclides from U.S. nuclear power reactors in 1972." "Radiation Data and Reports" 15 (August 1974): 477-482.

U.S. National Council on Radiation Protection and Measurements. "Alpha emitting particles in lungs." NCRP Report No. 46. Washington D.C.: NCRP, 1975.

Radiation Protection Criteria and Regulations

"Atomic energy control regulations." "Canada Gazette Pt. II." 108 (June 1974): 1783-1802.

"Atomic Energy Control Regulations." "Canada Gazette Part II." 112 (January 1978): 406-411.

Atomic Energy Control Board. "Excerpt from the 10th amendment (effective 30 August, 1974) of: "Regulations for the transportation of dangerous commodities by rail" issued by the Canadian Transport Commission." Ottawa: AECB, n.d.

"Atomic Energy Control Board transportation of radioactive materials." 15 November, 1976.

Canada, Dept. of National Health and Welfare, Health Protection Branch. "Environmental radioactivity in Canada, January - March 1977." Radiological monitoring quarterly report. Ottawa: Dept. of National Health and Welfare, 1977.

Canada, House of Commons. "Nuclear control and administration act, Bill C-14," 1st reading. 3rd sess., 30th parl., 26 Elizabeth II, 1977.

Canada, Transport Dept., Canadian Air Transportation Administration. "Carriage of dangerous goods and magnetized materials." "Notam" A-1/76, 1 June, 1976.

Canadian Transport Commission. "Regulations for the transportation of dangerous commodities by rail." Annex "C" to schedule to general order no. 1974-1-rail. Ottawa: Information Canada, 1974.

"Dangerous goods shipping regulations, amendment." "Canada Gazette Pt. II" 107 (June 1973): 1456.

International Commission on Radiological Protection. "Implications of commission recommendations that doses be kept as low as readily achievable." ICRP Publication 22. Toronto: Permagon Press, 1973.

International Commission on Radiological Protection. "Recommendations of the international commission on radiological protection." ICRP Publication 9. Toronto: Permagon Press, 1966.

International Commission on Radiological Protection. "Recommendations of the international commission on radiological protection." ICRP Publication 26. Oxford: Permagon Press, 1977.

"Prohibited mail regulations." "Canada Gazette Pt. II." 106 (December 1972): 2061-2063.

Taylor, Laurison S. "The origin and significance of radiation dose limits for the population." WASH-1336. Washington, D.C.: U.S. Atomic Energy Commission, Division of Biomedical and Environmental Research, 1973.

Taylor, Lauriston S. "Radiation Protection Standards" Cleveland, Ohio: Chemical Rubber Company Press, 1971.

U.S. Department of Commerce, National Bureau of Standards. "Maximum permissible body burdens and maximum permissible concentrations of radionuclides in air and in water for occupational exposure." National Committee on Radiation Protection Report No. 22. National Bureau of Standards Handbook 69. n.p., National Bureau of Standards, n.d.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Draft-Environmental statement for a proposed rulemaking action concerning environmental radiation protection requirements for normal operations of activities in the uranium fuel cycle." Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1975.

U.S. Environmental Protection Agency. Office of Radiation Programs. "National radiation protection program strategy-draft". EPA-520/7-75-007. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1975.

U.S. National Council on Radiation Protection and Measurements. "Basic radiation protection criteria." NCRP Report No. 39. Washington, D.C.: NCRP, 1971.

U.S. National Council on Radiation Protection and Measurements. "Review of the current state of radiation protection philosophy." NCRP Report No. 43. Washington, D.C.: NCRP, 1975.

Wong, K.Y. "Basis for the derived limits for the release of radionuclides in gaseous and liquid effluents from Ontario Hydro's nuclear stations." HPD-73-6. Toronto: Ontario Hydro, 1973.

Monitoring

American National Standards Institute, Inc. "American national standard guide to sampling airborne radioactive materials in nuclear facilities." New York: ANSI, 1970.

Bar-Shalom, Y., et al. "Handbook of statistical tests for evaluating employee exposure to air contaminants." Cincinnati, Ohio: U.S. National Institute for Occupational Safety and Health. Division of Laboratories and Criteria Development, 1975.

Bernhardt, D.E.; Johns, F.B.; and Kaufmann, R.F. "Radon exhalation from uranium mill tailings piles, description and verification of the measurement method." Las Vegas, Nevada: U.S. Environmental Protection Agency, Office of Radiation Programs, 1975.

Breslin, A.J. "Guidance for air sampling at nuclear facilities." HASL-312. New York: Health and Safety Laboratory, Energy Research and Development Administration, 1976.

Budnitz, Robert J. "Radon-222 and its daughters - a review of instrumentation for occupational and environmental monitoring." "Health Physics" 26 (February 1974): 145-163.

Canada, Atomic Energy Control Board. "Guide for licensing of radioactive waste management." "Information Bulletin" 74-1 (January 1974).

Countess, Richard J. "Measurement of ^{222}Rn flux with charcoal canisters." "Atomic Industrial Forum proceedings, Albuquerque, New Mexico, 1977." n.p., n.d.

Douglas, Richard L., and Hans, Jr., Joseph M. "Gamma radiation surveys at inactive uranium mill sites." Technical Note ORP/LV-75-5. Las Vegas, Nevada: U.S. Environmental Protection Agency, Office of Radiation Programs, 1975.

Duggan, M.J., and Howell, D.M. "The measurement of the unattached fraction of airborne RaA." "Health Physics" 17 (1969): 423-427.

Franklin, J.C. et al. "Data-acquisition system for radon monitoring." Report of Investigations 8100. Washington, D.C.: U.S. Dept. of the Interior, 1976.

George, Andreas C. "Scintillation flasks for the determination of low level concentrations of radon." "Health physics symposium, 9th midyear, proceedings, Denver, 1976." n.p., n.d.

Harley, N.H., and Pasternack, B.S. "The rapid estimation of radon daughters working levels when daughter equilibrium is unknown." "Health Physics" 17 (1969): 109-114.

International Atomic Energy Agency. "Handbook on calibration of radiation protection monitoring instruments." Technical Report Series No. 133. Vienna: IAEA., 1971.

"International Symposium on Rapid Methods for Measurement of Radioactivity in the Environment, Neuherberg bei Munchen, 1971." Vienna: International Atomic Energy Agency, 1971.

Jonassen, Niels, and Clements, William E. "Determination of radon-222 concentrations by an integrated count method." "Health Physics" 27 (October 1974): 347-351.

Kelkar, D.N., and Joshi, P.V. "A rapid method for estimating radium and radon in water." "Health Physics" 17 (1969): 253-257.

Kiefer, Hans, and Maushart, Rupprecht. "Radiation Protection Measurement." Translated by Ralf Friese. Toronto: Permagon Press, 1972.

Kusnetz, Howard L. "Radon daughters in mine atmospheres, - a field method for determining concentrations." "Industrial Hygiene Quarterly" (March 1956): 85-88.

Lawrence Berkeley Laboratory. Environmental Instrumentation Group. "Instrumentation for Environmental Monitoring." 3 Vol. Berkeley, California: Lawrence Berkeley Lab., 1976.

Lucas, Henry F. "Improved low-level alpha-scintillation counter for radon." "The Review of Scientific Instruments" 28 (September 1957): 680-683.

Marley, Merton R.; Beene, Harlow; and Geiger, Eric L. "Continuous radon progeny and gas monitor." Sante Fe, New Mexico: Eberline Instrument Corp., 1977.

Moeller, D.W. et al. "Environmental surveillance for nuclear facilities." "Nuclear Safety" 19 (January February 1978): 66-79.

Newstein, H.; Cohen, L.D.; and Krablin, R. "An automated atmospheric radon sampling system." "Atmospheric Environment" 5 (1971): 823-831.

"Objectives and design of environmental monitoring programmes for radioactive contaminants." Safety series No. 41. Vienna: International Atomic Energy Agency, 1975.

Partridge, J.E. et al. "A comparison of CaF_2:Mn and LiF thermoluminecent dosimeters for environmental radiation monitoring." EPA 520/5-73-006. Washington, D.C.: U.S. Environmental Protection Agency, Office of Radiation Programs, 1973.

Perkins, R.W., and Thomas, C.W. "Direct measurement of radionuclides in uranium mill tailings, ores and dust." Richland, Washington: Battelle, Pacific Northwest Division, 1976.

Pohl, Egon, and Pohl-Ruling, Johanna. "Determination of environmental or occupational Rn-222 in air and water and Ra-226 in water with feasible and rapid methods of sampling and measurement." "Health Physics" 31 (October 1976): 343-348.

Rock, R.L. "Sampling mine atmospheres for potential alpha energy due to the presence of radon-220 (thoron) daughters." Informational Report 1015. Washington, D.C.: U.S. Dept. of the Interior, Mining Enforcement and Safety Administration, 1975.

Strong, J.C., and Duggan, M.J. "The effect of the presence of thoron daughters on the measurement of radon daughter concentrations." "Health Physics" 25 (September 1973): 299-300.

Taniguchi, H. "Present practices of the Department of National Health and Welfare for the measurement of radon and daughter products." "Specialist meeting on personal dosimetry and area monitoring suitable for radon and daughter products, Elliot Lake, Ont., 1976." n.p., Organization for Economic Cooperation and Development, n.d.

Tappan, J. Tell. "Grab sampling: methods and interpretation." Grand Junction, Colorado: Combustion Engineering, Inc., n.d.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Environmental radioactivity surveillance guide." Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1972.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiation Protection Activities 1975." EPA-520/7-76-004. Washington, D.C.: U.S. EPA, Office of Radiation Programs, 1976.

U.S. Environmental Protection Agency, Office of Radiation Programs. "Radiation Protection Activities 1976." EPA-520/4-77-005. Washington, D.C.: U.S. EPA Office of Radiation Programs, 1977.

Voice of Women. "Fallout monitoring in Canada - Brief to the minister of national health and welfare." Toronto: Voice of Women, 1963.

Wade, James E. and Cunningham, G.E. "Radiation monitoring, a programmed instruction book." Oak Ridge, Tennessee: U.S. Atomic Energy Commission, Technical Information Center, 1967.

Waters, John R., and Howard, B.Y. "Calibration of instrument for measurement of radon concentrations in mine atmospheres." "Health Physics" 16 (1969): 657-659.

APPENDIX IV

TERMS OF REFERENCE

Schedule One
Contractor's Work Programme

The contractor will undertake to provide the Ministry of the Environment with an in-depth comprehensive report on radioactive substances, covering all aspects which are relevant to the role of these substances as environmental pollutants in Ontario. The report should represent a state-of-the-art summary and review of up-to-date, scientific and technical information. The information will be obtained by means of literature searches and from a reading of current literature, and be supplemented as required by discussions with knowledgeable professional staff in the university, government, and industrial communities. The information and data must be as current as reasonable access to scientific, governmental, and industrial sources allows, and should be the most reliable information that is available. Although the contractor is not expected to reconcile conflicting data, he should endeavour to provide some evaluation and synthesis of the collected information. The contractor is not expected to generate new laboratory data, or engage in ambient environmental surveys or source testing programmes.

The comprehensive report should be prepared in sufficient detail to serve as a basis for Ministry policy determination, control/abatement program design, and otherwise sound decision-making on future Ministry activities.

The report must give consideration to the following areas:

1. Potential Sources of Environmental Emissions and Discharges:

   (a) Description of industries in Ontario which are potential sources (e.g., mining, milling and refining of uranium ore, nuclear fuel fabrication, nuclear power generation).

   (b) Description of industrial operations and processes (including radioactive waste management) which are potential sources. Identification of points of emissions or discharges, and types of radioactive pollutants.

   (c) Estimates, specific to Ontario industries, of potential emissions or discharges of radioactive substances to the environment, as derived from a knowledge of the industrial operations, control equipment and practices in use, and/or published values of source strengths or emission factors.

(d) Assessment of the population size potentially exposed to the estimated emissions.

2. Process and Control Technology for Reducing Radionuclide Releases:

(a) Description and evaluation of available control apparatus and practices designed to eliminate or minimize exposure to radioactive substances by workers and the public. Apparatus and practices in current use by Ontario industries.

(b) Identification of necessary research and development for improved control and abatement technology.

(c) Cost-benefit considerations associated with radiation protection.

(d) Identification of need for data from source discharge monitoring, and recommendations for specific programmes.

3. Distribution, Persistence, and Fate of the Identified Pollutants in the Environment

(a) Physical, chemical, radioactive, and toxicological characteristics and properties of the identified pollutants in the environment. Changes in characteristics and properties with time after release.

(b) Pathways in the environment (air, water, soil, biota). Residence times. Dispersal characteristics. Principal removal mechanisms. Potential for long-range transport.

(c) Synergistic effect of other substances simultaneously present (e.g., particulates).

4. Health Effects:

(a) Toxicity of the identified radioactive pollutants and mechanisms for radiation damage (metabolic characteristics, biological half-life, critical organ). Radiation dose assessment modelling for occupational and environmental situations. Direct and indirect exposure pathways.

(b) Documented effects on humans, particularly as a result of low dose levels and extended exposure times. Sources of information (epidemiological surveys, occupational exposure, etc.).

(c) Instances of community and occupational exposure documented in the literature.

5. Standards and Criteria:

(a) Principles and procedures used by various agencies in the

setting of radiation protection standards and criteria. Evaluation.

(b) Existing environmental and occupational standards and criteria for radioactive substances in Ontario and elsewhere. Evaluation.

6. Environmental Concentrations:

(a) Published values of radiation levels and environmental concentrations of radioactive substances for specific sources (occupational, ambient environment). Environmental pollution "episodes". Background (natural) radiation levels.

(b) Dispersion modelling procedures for predictions of environmental quality with respect to radioactive exposure.

(c) Environmental concentrations and radiation levels (in air, water, soil, biota) specific to Ontario industries.

(d) Need for monitoring surveys in vicinity of industrial sources and recommendations for specific programmes.

7. Sampling and Analytical Techniques:

(a) Description and evaluation of available apparatus and techniques for various parameters (concentrations, radiation levels, cumulative dosages, particulate size distributions, etc.) of the identified pollutants in gaseous or particulate form.

(b) Accuracy, sensitivity, and detection limits of available apparatus and techniques. Adequacy of techniques. Identification of research and development needs. Recommendations.

(c) Apparatus and techniques currently used by Ontario Ministries (Environment, Labour) and other environmental agencies.

8. Recommendations:

(a) Surveys in the vicinity of potential sources (air, water, soil).

(b) Emission inventories including source testing programs.

(c) Epidemiological studies.

(d) Research and development for control/abatement technology and sampling/analytical techniques.

Other relevant topics with regard to the environmental aspects of radioactive substances should not be excluded. Also, the points outlined for each of the above topics are intended only as guides and should not be regarded as restrictive. The contractor must treat each study area as comprehensively as possible. Although all topics outlined above (and additional study areas, as required) are considered important, topics 1,2,3,4,5,8 should be assigned the highest priority.

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